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THESIS

COMMON SUBMARINE RADIO ROOM: A CASE STUDY OF A SYSTEM OF SYSTEMS APPROACH

by

Mitchell D. Seime

September 2014

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Common Submarine Radio Room is the latest step by the submarine force towards implementing a modular approach using an open systems architecture and increasing the automation of communications network management. Introduced on the Virginia class submarines as a commercially furnished design, it has since transferred to government management as an acquisition category two program, replicated on the other four submarine classes and planned for the Ohio replacement submarine. The current design and development approach is done in a serial fashion, with a version completed for each class before beginning the development of the next. The increasing pace of technology due to obsolescence, new capabilities, demands to support individual program development and fielding schedules create conflicting priorities between fielding capability and maintaining effective configuration management of a version. Common Submarine Radio Room version uses a system of systems engineering and integration approach to balance the demands of each stakeholder and deliver capability. This approach will be examined as a case study to identify the benefits and consequences of design, testing, production, deployment, and sustainment.

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COMMON SUBMARINE RADIO ROOM: A CASE STUDY OF A SYSTEM OF SYSTEMS APPROACH

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ABSTRACT

Common Submarine Radio Room is the latest step by the submarine force towards implementing a modular approach using an open systems architecture and increasing the automation of communications network management. Introduced on the Virginia class submarines as a commercially furnished design, it has since transferred to government management as an acquisition category two program, replicated on the other four submarine classes and planned for the Ohio replacement submarine. The current design and development approach is done in a serial fashion, with a version completed for each class before beginning the development of the next. The increasing pace of technology due to obsolescence, new capabilities, demands to support individual program development and fielding schedules create conflicting priorities between fielding capability and maintaining effective configuration management of a version. Common Submarine Radio Room version uses a system of systems engineering and integration approach to balance the demands of each stakeholder and deliver capability. This approach will be examined as a case study to identify the benefits and consequences of design, testing, production, deployment, and sustainment.

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

ACAT	acquisition category
ADNS	automated digital networking system
ADW	advanced digital waveform
AIT	alteration installation team
A_o	operational availability
AOA	analysis of alternatives
AP	acquisition plan
AS	acquisition strategy
ASN(RDA)	Assistant Secretary of the Navy for Research, Development and Acquisition
BBS	baseband switch
BCA	broadcast control authority
BGIXS	battle group information exchange system
C&M	control and management
C2	command and control
C4I	command, control, communications, computers and intelligence
C4ISR	command, control, computers, intelligence, surveillance and reconnaissance
CANES	consolidated afloat network enterprise system
CDR	critical design review
CMMI	capability maturity model integration
CNO	Chief of Naval Operations
COE	common operating environment
COMSUBFOR	Commander, Submarine Forces
CONOPS	concept of operations
COP	common operational picture
COTS	commercial-off-the-shelf
CPD	capabilities production document
CRD	capstone requirements document
CRR	common radio room

CSG	carrier strike group
CSRR	common submarine radio room
CUE	crypto universal enclosure
DAG	defense acquisition guide
DASN (AT&L)	Deputy Assistant Secretary of the Navy for Acquisition, Technology and Logistics
DASN (RDT&E)	Deputy Assistant Secretary of the Navy for Research, Development, Testing and Evaluation
DAU	Defense Acquisition University
DIACAP	defense information assurance certification and accreditation program
DIARMF	defense information assurance risk management framework
DII	defense information infrastructure
DMR	digital modular radio
DOD	Department of Defense
DOT&E	Director, Operational Testing and Evaluation
DSCS	Defense satellite communications system
DSMC	Defense Systems Management College
DUSW	design for undersea warfare
EAM	emergency action message
ECR	enterprise change request
EHF	extremely high frequency
ESG	expeditionary strike group
ETR	Submarine communications electronics technician
FRD	Fleet readiness directorate
FSBS	fleet submarine broadcast system
FY	fiscal year
GBS	global broadcast service
GCCS-M	global command and control system-maritime
GOTS	government-off-the-shelf
GPS	global positioning system
GSFC	Goddard Space Flight Center
HF	high frequency

IBR	integrated baseline review
IC	intelligence community
IFF	identify friend or foe
ILS	integrated logistics support
IMCS	integrated maritime communications system
IMO	installation management office
INCOSE	International Council on Systems Engineering
INM	integrated network manager
IOC	initial operational capability
IP	internet protocol
IRR	integrated radio room
ISEA	in service engineering activity
ISR	intelligence, surveillance and reconnaissance
ITTA	information technology technical authority
ITS	Information systems technician submarines
IW	integrated waveform
JCIDS	joint capabilities and integration development system
JCS	Joint Chiefs of Staff
JMCIS	joint maritime command information system
JMCOMS	joint maritime communications systems
JP	joint pub
JTRS	joint tactical radio system
LA	Los Angeles
LAN	local area network
LCS	littoral combat ship
LF	low frequency
LOS	line of sight
LSS	lean six sigma
MCAP	medium data rate channel access protocol
MILSATCOM	military satellite communications
MILSTAR	military strategic and tactical relay system
MINI-DAMA	miniaturized demand assigned multiple access

MIW	mine warfare
MNS	mission needs statement
MRTS	multi reconfigurable training system
MSTI	miniature seeker technology integration
MUOS	mobile user objective system
NASA	National Air and Space Administration
NAVAIR	Naval Air Systems Command
NAVMACS	Navy modular automated communications system
NAVSEA	Naval Sea Systems Command
NC3	nuclear command, control and communications
NCA	National Command Authority
NDI	non developmental item
NETWARCOM	Naval Networks Warfare Command
NMT	Navy multiband terminal
NUWC	Naval Undersea Warfare Center
OE	outboard electronics
ORD	operational requirements document
ORP	Ohio replacement program
OSIC	onsite installation coordinator
OSR	onsite representative
OT	operational test
OSA	open systems architecture
OTCIXS	officer in tactical command information exchange system
OUSD (AT&L)	Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics
PDR	preliminary design review
PEO C4I	Program Executive Office for Command, Control, Communications, Computers and Intelligence
PEO IWS	Program Executive Office for Integrated Warfare Systems
PEO SUB	Program Executive Office Submarines
PIM	platform installation manager
PITCO	pre-installation testing and check out

PMA	program management air
PMW	program management warfare
POR	program of record
PSA	post shakedown availability
RF	radio frequency
RFDACS	radio frequency distribution and control system
SAT	systems acceptance test
SATCOM	satellite communications
SBCS	submarine baseband circuit switch
SCI	sensitive compartmented information
SCSS	submarine communications support system
SD	strategic deterrence
SDVT	systems design verification test
SE	systems engineering
SEBOK	systems engineering book of knowledge
SETR	systems engineering technical review
SI	special intelligence
SLVR	submarine low frequency/ very low frequency versa modular euro bus receiver
SOF	special operations forces
SOS	system of systems
SOSE	system of systems engineering
SOVT	systems operational verification test
SPAWAR	Space and Naval Warfare Systems Command
SSBN	submersible ship, ballistic, nuclear
SSC LANT	SPAWAR Systems Center Atlantic
SSC PAC	SPAWAR Systems Center Pacific
SSGN	submersible ship, guided missile, nuclear
SSIXS	submarine satellite information exchange system
SSN	submersible ship, nuclear
SSP	Strategic System Programs
SUBECS	submarine exterior communications system

SUBHDR	submarine high data rate
SUBLAN	submarine local area network
SUBSMS	submarine single messaging system
SUW	surface warfare
SW	Seawolf
SWFTS	submarine warfare federated tactical system
TACAMO	take charge and move out
TCM	targeting change message
TEMP	test and evaluation master plan
TFDS	time frequency distribution system
TI/APB	technical insertion/advanced processor build
TIP	time division multiple access interface processor
TOC	total ownership cost
UHF	ultra-high frequency
USD	Undersecretary of Defense
USW	undersea warfare
V1	version 1
V2	version 2
V3	version 3
VA	Virginia
VERDIN	VLF Digital Information Network
VHF	very high frequency
VLF	very low frequency
VSA	value stream analysis
WAN	wide area network

EXECUTIVE SUMMARY

The Department of Defense (DOD) is responsible for acquiring capabilities for the submarine force to support a myriad of missions. Historically systems were acquired and deployed to support a specific capability. Command, Control, Communications, Computers and Intelligence (C4I) capabilities within the submarine force have evolved over the last century as new technologies increase access to the RF spectrum and available bandwidth. As systems evolve and interoperability becomes more critical, these are being integrated into systems of systems (SOS) to provide capabilities that were previously not available. This thesis used a case study approach to examine the Common Submarine Radio Room (CSRR) as a SOS. The following recommendations, or learning principles, where identified as applicable to the development and management of a system of systems. These are:

- Clearly define the requirements for the entire SOS life cycle.
- Avoid building a SOS before defining the architecture.
- The design of an acknowledged SOS must be shared to the maximum extent practicable.
- System of systems must control interfaces.
- Allow the SOS to go fast when possible, otherwise go slow.
- Account for all of the "ilities" when developing the system of systems design.
- Consider how the SOS will be tested.
- Acknowledge SOSs can change unexpectedly.
- Understand perfect is the enemy of good enough.
- Building a SOS requires building effective relationships.
- Regardless of what the SOS is built for it must be able to support the customers. Keep them in mind.
- Effective SOSs require effective teams that are engaged, motivated, and productive.

The research determined CSRR exhibited the characteristics of an acknowledged SOS. Common Submarine Radio Room is made up of a number of independent systems capable of operating independently and has their own requirements, funding, and

management. These systems have their own engineering and sustainment approaches. Each system is fully operational within its established requirements but additional capabilities are not fully realized until they are integrated into a SOS (Vaneman 2012). As a SOS, CSRR provides redundancy in several ways. If a communications path is not available another can be selected. If there is a network failure, alternate means to reroute or restore network management exist. Centralized control and management provides more efficient use of resources and improved situational awareness.

System of systems design and implementation require a more holistic view. Developing and managing a mission or platform SOS extends beyond the activities involved for a single system. Managing a SOS is a complex endeavor as competing demands of the individual systems must be addressed and balanced against the requirements and objectives of whole SOS. Working with an acknowledged SOS, such as CSRR, means changes to the constituent systems must be evaluated and integrated to avoid a disruption or degradation of the whole SOS capability. New capabilities that result from integrating several systems into a SOS can create confusion as to who owns these new capabilities. Program managers have responsibility for their specific system whereas most SOS have no assigned manager. Most programs are acquired using clearly defined capability requirements. Systems of systems requirements and characteristics can be more complex and amorphous. A SOS program with an assigned manager must work continuously with all of the individual programs to minimize the impact of one program attempting to optimize at the expense of the others. Depending on the systems involved and the type of SOS, programmatic and systems engineering decisions may occur at lower levels that are not in the best interests of the overall SOS. Understanding the characteristics of a SOS and the engineering principles involved are key factors to successfully delivering operational capabilities from a group of individual systems. Only recently has DOD acknowledged acquisition of SOS capability requires a much more holistic approach (Director, Systems and Software Engineering 2008).

This thesis researched the following questions to regarding CSRR.

1. What is CSRR and what characteristics classify it is as a SOS?

2. What are the benefits and challenges of developing, designing, producing, deploying, and sustaining CSRR as a SOS?
3. What best practices have been identified and implemented in the CSRR program and what benefits have been realized in terms of cost, performance, and schedule?
4. What lessons learned can be applied to future versions of CSRR and common radio room (CRR) for surface combatants?

The research questions were bounded to examine the history leading up to CSRR to understand how evolving requirements and capabilities led to its development. The organizational structure of the CSRR program and stakeholder relationships, management of an SOS architecture and the benefits and drawbacks, initiatives to improve cost, schedule, and performance were also examined. Last, the ability to meet future mission requirements was evaluated.

The methodology used a Friedman and Sage (2003) framework for providing the necessary background and context to understand the activities involved in managing a SOS and their impacts. Capturing the lessons provide opportunities to share them with others. The methodology used the following steps. Other case studies were reviewed to determine if previous work had been accomplished and if there was merit to using this approach. The review confirmed similar case studies had been written by the Air Force and National Aeronautical and Space Administration (NASA) (Chislaghi, Dyer and Free 2010; Grenville, Kleiner and Newcomb 2004; Griffin 2004; Griffin and Kinnu 2007; Jacques and Strouble 2010; Kinzig 2010) and several addressed SOS issues (Collens and Krause 2005; Mattice 2003; O'Brien and Griffin 2007). The Air Force recognized the need to extract lessons learned from a number of their programs after acknowledging much of their systems engineering expertise had atrophied. Additionally, NASA faced a similar situation when it recognized that its workforce, which consists of highly specialized and experienced engineers, scientists and technicians, had a significant percentage approaching retirement. Capturing their knowledge and experience in order to share it with others resulted in a series of case studies analyzing Air Force and NASA programs.

Searches for Navy and specifically command, control, computers, communications, and intelligence (C4I) case studies revealed few existed for C4I systems. Further searches of the Program Executive Office (PEO) C4I archives had none for PEO C4I managed systems. Most DOD documentation regarding SOS principles, characteristics, requirements and acquisition has been developed only recently. The CSRR program documentation provided insight to the history, requirements and policies for managing the CSRR program. Review of various team documents and interviews with subject matter experts from the engineering and production teams were conducted to capture insight about developing and managing a SOS program and the challenges of coordinating with the constituent systems. The compiled information was then synthesized to identify lessons learned, or learning principles, develop conclusions, and make recommendations for further investigation.

Developing case studies meets several objectives. Capturing the information about a particular event, person, or object can reveal the significant issues or lessons learned. These lessons learned can be used as real life examples to train engineers and program managers. Application of these lessons can aid in avoiding repeating mistakes, or identify similar opportunities to improve cost, schedule and performance. The use of case studies by the Navy is not clearly evident but the Air Force and NASA have recognized their value for identifying important lessons. Capturing the knowledge transfers it from a tacit form to a more easily accessible explicit format. The lack of case studies about C4I systems, particularly those managed by PEO C4I, identified the value of examining a program within their portfolio.

CSRR revealed managing a SOS program has a number of challenges. Most DOD SOSs are classified as an acknowledged type of SOS since they are composed of individual programs with their own program and funding responsibilities. Acknowledged SOSs, such as CSRR, also have their own requirements and funding, but these must be synchronized with the other systems within the CSRR architecture. Each individual system can cause emergence to other systems as components are added or removed. Effective governance is required to balance the requirements of the constituent systems composing CSRR within the SOS architecture (Vaneman and Jaskot 2013). Changes to

any of the constituent systems are managed by their respective programs but must be evaluated by the overarching SOS to avoid or minimize degradation or disruption of capability. Attempting to optimize one system over the others can be detrimental to the overall system of systems. An advantage of a SOS is the redundancy not available from a single system (Jamshidi 2009). Disruption of a communications or network path can be mitigated by using an alternate means.

Systems engineering and SOS engineering share many characteristics but differ in their approach (Director, Systems and Software Engineering 2008). A system engineer will strive to develop a single system based on clearly defined requirements. System of systems requirements are more generalized and the SOS engineer is responsible for integrating the capabilities of two or more systems. Systems have a fairly defined life cycle. System of systems tend to be more perpetual. The various life cycles typically are not aligned so a system of systems will possess an evolutionary life cycle which changes but does not end. A system normally has a single program manager while a system of systems, depending on the type, may not have one at all.

Examination of CSRR as a program, process and product provided insight to the integration approach and the domains related to requirements, architecture, design, integration and management. As a program, understanding the SOS and balancing them with the constituent systems is key to delivering the right capabilities to the user. From a product consideration, effective management of interfaces is necessary to enabling the right capabilities as systems are integrated. As a process, implementing SOS engineering processes acknowledges emergence may occur. All of these have a bearing on performing successful SOS engineering.

Common Submarine Radio Room is the culmination of these efforts while introducing open systems architecture designed to combine and leverage its constituent systems to deliver capabilities not possible in an individual manner. The approach for developing CSRR has evolved as well, moving from developing a specific increment version for each class to the point where a single version delivers a complete core capability capable of accounting for any unique platform characteristics.

LIST OF REFERENCES

Director, Systems and Software Engineering. 2008. *Systems Engineering Guide for Systems of Systems* Version 1.0. Washington, DC: Office of the Deputy Under Secretary of Defense Acquisition, Technology and Logistics (AT&L). Accessed July 27, 2014. http://www.acq.osd.mil/se/docs/SE-Guide-for-SoS.pdf

Chislaghi, Don, Richard Dyer and Jay Free. 2010. *KC-135 Simulator Systems Engineering Case Study*. Wright Patterson, OH: Air Force Center for Systems Engineering, Air Force Institute of Technology. Accessed August 02, 2014. www.dtic.mil/dtic/tr/fulltext/u2/a538401.pdf

Collens, Josiah and Bob Krause. 2005. T*heater Battle Management Core System*. Wright Patterson, OH: Air Force Center for Systems Engineering, Air Force Institute of Technology. Accessed June 20, 2014. https://acc.dau.mil/adl/en-US/37601/file/9106/Theater%20Battle%20Management%20Core%20System%20SE%20Case%20Study%20-%20Collens%20_%20Krause.pdf

Friedman, George and Andrew Sage. 2003. "Case Studies of Systems Engineering and Management in Systems Acquisition." *System Engineering* 7(1): 84–96. Accessed July 13, 2014. http://onlinelibrary.wiley.com.libproxy.nps.edu/doi/10.1002/sys.10057/pdf

Grenville, Delia, Brian Kleiner, and John Newcomb. 2004. *Miniature Seeker Technology Integration, Optimizing the Whole System*. Blacksburg, VA: Virginia Polytechnic Institute. Accessed April 04, 2014. http://www.nasa.gov/pdf/293212main_58529main_msti_casestudy_042604.pdf

Griffin, John. 2004. *C-5A Galaxy Systems Engineering Case Study*. Wright Patterson, OH: Air Force Center for Systems Engineering, Air Force Institute of Technology. Accessed August 02, 2014. https://acc.dau.mil/adl/en-US/37598/file/9103/C-5A%20Galaxy%20SE%20Case%20Study.pdf

Jamshidi, Mohammad, ed. 2009. S*ystem of Systems Engineering: Innovations for the 21st Century*. Hoboken, NJ: Wiley.

Kinzig, Bill. 2010. *Global Hawk Systems Engineering Case Study*. Wright Patterson, OH: Air Force Center for Systems Engineering, Air Force Institute of Technology. Accessed April 04, 2014. www.dtic.mil/dtic/tr/fulltext/u2/a538761.pdf

Mattice, James. 2003. *Hubble Space Telescope Systems Engineering Case Study*. Wright Patterson, OH: Air Force Center for Systems Engineering, Air Force Institute of Technology. Accessed August 02, 2014. https://acc.dau.mil/adl/en-US/37600/file/9105/Hubble%20Space%20Telescope%20SE%20Case%20Study%20-%20JJ%20Mattice.pdf

O'Brien, Patrick and John Griffin. 2007. *Global Positioning System Systems Engineering Case Study*. Wright-Patterson Air Force Base, OH: Air Force Center for Systems Engineering Air Force Institute of Technology. Accessed April 04, 2014. http://www.afit.edu/cse/casedocs/files/GPS%20SE%20Study%20Final%20Report%20_4%20Oct%2007.pdf

Richey, G. Keith. 2005. *F-111 Systems Engineering Case Study*. Wright-Patterson AFB, OH: Center for Systems Engineering at the Air Force Institute of Technology. Accessed July 23, 2014. https://acc.dau.mil/CommunityBrowser.aspx?id=37599

Stockman, Bill, Joe Boyle, and John Bacon. 2010. *International Space Station Systems Engineering Case Study*. Wright Patterson, OH: Air Force Center for Systems Engineering, Air Force Institute of Technology. Accessed July 23, 2014. http://spacese.spacegrant.org/uploads/images/ISS/ISS%20SE%20Case%20Study.pdf

Vaneman, Warren. 2012. *A Framework for Establishing System of Systems Governance*. Arlington, VA: 16th Annual Systems Engineering Conference. Accessed July 12, 2014. http://dtic.mil/ndia/2013system/TH16038_Vaneman.pdf

Vaneman, Warren and Roger Jaskot. 2013. "A criteria-based framework for establishing system of systems governance." In *Systems Conference (SysCon), 2013 IEEE International*, 491–496. 7, doi 10.1109/SysCon.2013.654992

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I. INTRODUCTION AND BACKGROUND

Today's submarine communications requirements continue to increase as bandwidth and network capacity expands. Interoperability challenges between the various communications systems throughout the U.S. military place additional burdens and vulnerabilities on the warfighter. While there are specific requirements which must be addressed, the overall capability of the communications systems must (a) rapidly adapt to changing demands while providing the right information to the right place at the right time, (b) protect it from interception and exploitation, and (c) deliver it in a format which can be actionable (Joint Chiefs of Staff [JCS] 2011). Achieving these basic objectives enable U.S. forces to accomplish their assigned missions.

The challenge of meeting the demands of the warfighter has forced individual command, control and communications systems to integrate more closely into large and complex system of systems. Many systems are developed without consideration of how they impact other systems or the operations and support infrastructure. Common Submarine Radio Room (CSRR) provides a programmatic path to oversee integration activities, an architecture supporting coordinated delivery of capabilities and physical products to achieve interoperability of individual systems across multiple submarine platforms.

The CSRR program is the latest effort by the submarine force to implement a holistic approach to design, build, certify, and deploy a command, control, communications, computers and intelligence (C4I) architecture as a system of systems composed of individually managed programs of record (POR). The CSRR program was established within the undersea integration program management warfare office (PMW770) to assume the lead systems integrator role for Program Executive Office for Command, Control, Communications, Computers and Intelligence (PEO C4I) programs planned for deployment to a submarine. Using a robust design, build, test and certify strategy the CSRR has successfully demonstrated it is operationally effective and suitable. Since the initial operating capability (IOC) in 2006, CSRR is fielded on all *Virginia* (VA), *Ohio* ballistic missile (SSBN), *Ohio* guided missile (SSGN), and *Seawolf*

(SW) platforms. The *Los Angeles* (LA) class began in 2012 and is planned to reach full operational capability (FOC) in fiscal year (FY) 2018. Common Submarine Radio Room as a product architecture and program strategy has demonstrated the effectiveness of integrating multiple products within the PEO C4I portfolio. Since the original increment one version zero CSRR has continued to evolve. Today increment one version three (V3) is being fielded to LA and VA platforms with SSBN, SSGN, and SW beginning in 2014.

The success of the CSRR program has spurred other warfare domains to examine how the CSRR architecture can be expanded to influence other platform architecture and engineering strategies and create a product line for the other communities within the U.S. Navy. In order to capture the lessons learned from the CSRR program this case study will analyze the history, concept of operations, systems engineering, the results and assessment of the benefits and costs. The lessons learned from the CSRR program as a system of systems engineering and integration activity can be identified and passed onto other programs. Acknowledgment by PEO C4I the CSRR model works serves as a key testament to the viability of using a system of systems design approach. Today PEO C4I is evaluating the idea of a "Common Radio Room" for surface combatants.

A. WHY A CASE STUDY?

Case studies provide the opportunity to capture and distribute valuable lessons learned. Case study approaches can vary in their format and goals. Case studies are used to perform the following (National Aeronautics and Space Administration [NASA] Goddard Space Flight Center [GSFC] 2011; Haskins 2012):

- Record mission or project successes or failures
- Lessons learned of a technical or programmatic nature
- Design decisions of what worked or did not work and the outcomes
- Incidents, near incidents and safety reminders
- Personal insights

Friedman and Sage (2003, 84–96) discuss how case studies can contribute to capturing the history of a program or event for systems engineering, systems management and acquisition. Case studies support teaching students about problems

experienced in the real world. Effective case studies capture lessons learned during the different phases of the program life cycle so they can be shared with others. Sharing in turn provide insight for future systems engineers and program managers tasked with developing and managing a system of systems program to understand the challenges and opportunities and how to avoid, minimize, or leverage them. The use of a case study framework provides an effective means to decompose the issues into a specific topic and responsibility.

B. PURPOSE OF THIS CASE STUDY

Research both online and available libraries identified there are few case studies concerning the application of system of systems (SOS). Many systems case studies exist but the concept of a SOS has only been widely acknowledged recently. This thesis will examine the CSRR program and attempt to provide lessons that can be applied to other SOS in terms of the following:

1. The history of submarine communications leading up to the CSRR program.
2. The organizational structure of the CSRR program.
3. The relationship with other programs of record and stakeholders.
4. SOS architecture management.
5. The advantages and disadvantages of the CSRR SOS approach within the various disciplines (e.g., development, modernization, integrated logistics support (ILS), training, sustainment, and information assurance (IA)).
6. Process improvement initiatives and their impact in regard to cost, schedule and performance.
7. CSRR's ability to meet future mission requirements while supporting current missions.

C. RESEARCH QUESTIONS

Research into the development of CSRR and management of a SOS identified several questions. This thesis will examine the following questions to provide a clearer understanding of how PEO C4I develops their individual programs and integrates them into a larger system of systems program such as CSRR.

1. What is CSRR and what characteristics classify it as a system of systems?

2. What are the benefits and challenges of developing, designing, producing, deploying, and sustaining CSRR as a SOS?
3. What best practices have been identified and implemented in the CSRR program and what benefits have been realized in terms of cost, performance, and schedule?
4. What lessons learned can be applied to future versions of CSRR and CRR for surface combatants?

D. SCOPE

This assessment will look at the CSRR program from the following perspective:

1. The development of submarine communications from its initial beginnings up through the deployment of CSRR increment one version three.
2. The organizational structure of the CSRR program to include the design and development group, production and installation group, ILS and training groups, IA groups, and sustainment group.
3. The version development process, its strengths and weaknesses.
4. SOS architecture management with other programs of record and portfolio capability management, the relationships with the other programs of record and the warfighter.
5. The advantages and disadvantages of the CSRR system of systems approach regarding ILS, training, production, installation (synchronization of installations into block upgrades), IA and sustainment.
6. Assessment of requirements in a changing environment with regard to the Undersea Connectivity Roadmap, Design for Undersea Warfare, PEO C4I Master Plan, and the way ahead for considering disruptive technologies.
7. An evaluation of the process improvement initiatives and their influence and impact in regard to cost, schedule and performance.
8. The future of CSRR in today's environment and tomorrow up through 2030.

E. METHODOLOGY

The methodology used in this case study consisted of the following activities.

1. Investigation into other case studies to determine if other researchers had performed similar work and confirm if a case study would be an appropriate approach. Review of other case studies did indicate similar work had been done but no specific case studies had been found specifically addressing specific programs as a SOS.
2. Investigation into Navy and specifically PEO C4I archives to determine if any case studies had been written.

3. Review of the DOD acquisition and program documentation regarding SOS, defense acquisition requirements, systems and system of systems principles.
4. Perform an in depth analysis of the CSRR program documentation, This includes the formal program documentation and minutes from the various integrated product teams (IPT) supporting the program.
5. Conducted selected interviews with subject matter experts (SME) with regard to developing and managing a SOS program and the individual systems supporting the SOS.
6. Synthesize the information to capture lessons learned (or learning principles), develop conclusions and make recommendations for further consideration. A derivative of the Friedman and Sage framework will be used since contractor involvement is limited.

F. EXPECTED BENEFITS OF THIS CASE STUDY

Warfighter capabilities increasingly involve using complex, disparate, and geographically separate systems. PEO C4I manages over 100 programs and many more projects and investigations. The importance of programs is determined by the acquisition category (ACAT) assigned which is primarily related to the expected program cost and not its complexity (Carter 2013, Encl 3). Every program manager wants to be successful in managing the activities and funding aligned to their program. Management of individual programs versus management by capability creates unexpected issues and friction as systems are deployed in different environments. Many programs fail to develop synergy with others to improve or expand their capabilities. Systems requirements and system of systems requirements often conflict forcing unexpected changes. For example an individual system may need to meet a higher availability requirement in order to help the SOS meet its availability threshold requirement.

The benefit of examining how the CSRR program is managed, the processes it developed, relationships with stakeholders, and its successes and failures can provide a guide for managing a complex SOS from development through evolution/modernization and sustainment.

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II. LITERATURE REVIEW

There is a great deal of literature available about systems, systems engineering, systems of systems engineering and the development and use of case studies. Available case studies of other government programs identify learning principles of the positive and negative aspects. A majority of CSRR program information is normally limited to what is developed within the program office to support its acquisition responsibilities. This includes the requirements documentation, engineering plans, test and evaluation plans, acquisition strategies, concept of operations, etc. Understanding the activities and events which led up to the development of CSRR look at how communications evolved from simple single function components to complex, multi-functional voice and information network nodes. These documents are important as each supports the systems engineering activities necessary for developing and managing an acquisition program.

This chapter will look at:

1. The background of submarine communications leading up to CSRR
2. Available CSRR program documentation to include acquisition, engineering, test and evaluation, logistics and information assurance (IA)
3. Available systems, systems engineering and system of systems engineering documentation
4. Systems engineering case studies

A search of the Dudley Knox Library for the term "Navy system engineering case studies" identified 96 possible candidates. Performing a more detailed search for a "'system of systems'" Navy engineering case study" identified only five hits. Using Google to perform a similar search generated over 25,000,000 possible results. Extending this further for the term "system of systems" narrowed the results to over 350,000. In each search, several of the example case studies were listed. The search for case studies identified those written by the Air Force and NASA. The Hubble space telescope (Mattice 2003), F-111 (Richey 2005), Global Hawk (Kinzig 2010), Theater Battle Management Core System (TBMCS) (Collens and Krause 2005), C-5 Galaxy (Griffin 2004) and several others were used in support of the research.

A. SUBMARINE COMMUNICATIONS BACKGROUND

The modern submarine force has been in existence since 1900. Since the beginning development of effective and reliable technology capable of supporting submarine command and control (C2) has always proved to be challenging. The invention of wireless telegraphy provided the ability to communicate between a submarine and another location. The U.S. Navy began experimenting with submarine communications in 1912 successfully testing the capability at a range of four nautical miles off Newport, Rhode Island (Howeth 1963, 513–546). Following World War One a 100 watt submarine transmitter, a model TM, provided the initial capability of a spark gap radio. At the same time, the Navy teamed with the Edison Society, Bureau of Standards, Hammond Laboratory and Marconi Telegraph to determine how to communicate with submarines. Demonstrations of different antennas and radios resulted in a combination capable of receiving very low frequency (VLF) signals from distances up to 3,000 miles (Howeth 1963, 319–335) while submerged at periscope depth. The 1920s saw the invention and expansion of high frequency (HF) communications with the Navy successfully demonstrating the technology to reliably communicate from ship to ship and ship to shore via voice. Navy leadership recognized their growing submarine force needed a reliable means to receive long range communications in all planned areas of operation. Another unintended aspect during the 1920s was the increase of commercial radio, which caused a clash between military and civil interests. The competition for access to the frequency spectrum drove investigation into using higher frequencies expanding into the very high frequency (VHF) and ultra- high frequency (UHF) spectrum (Howeth 1963, 397–402).

Communications continued to play a key role during World War Two. Vice Admiral Thomas Hart, commander of the Asiatic Fleet, used low frequency (LF) radio to initiate unrestricted submarine warfare following the attack on Pearl Harbor. At the time high frequency was acknowledged as the primary long haul communications path. Unfortunately, HF suffered from interference caused by weather, sun spots, diurnal effects, and could not be utilized while submerged. U.S. submarines copied the German model of wolf packs, where submarines coordinated their operations, which in turn

identified a need for short range communications. Additional threats from attacks by friendly aircraft emphasized the need as well. The deployment of VHF radios addressed this need near the end of the war and the post war period (Clay 2008). Figure 1 illustrates the typical radio room of a WWII fleet submarine.

The Cold War and nuclear arms race with the Soviet Union created requirements for greater C2 and weapons systems capabilities, driving further advances in submarine communications. However, all systems up to this point were still a single function, stovepipe capability. The expansion of the VLF usage and establishment of transmitters capable of a global reach provided one reliable path for supporting communications with submarines. Additional communications circuits were added as the submarine missions expanded and additional radio frequency (RF) spectrum became available. The USS *Nautilus* radio room shown in Figure 2 is more modular but still maintains unique functions within a specific box.

Figure 1. WW2 USS *Torsk* Radio Room (from Hummel n.d.)

Figure 2. Replica of USS *Nautilus* Radio Room (from Amateur Radio Relay League 2009)

Deployment of the SSBN USS *George Washington* in late 1960 (Yarnell n.d.), shown in Figure 3 was supported with the capabilities of the Fixed Submarine Broadcast System (FSBS) in the VLF spectrum and establishment of transmitters capable of a global reach to provide reliable one way continuous communications with the National Command Authority (NCA). The VLF Digital Information Network (VERDIN) served as the shipboard system of the FSBS to receive and process messages to the message processor. The VERDIN systems were phased out in the late 1990s to be replaced with the Submarine LF/VLF Versa Modular Eurobus (VME) Receiver (SLVR).

Figure 3. USS *George Washington* SSBN-598 (from Yarnell n.d.)

The 1960s ushered in the era of global satellite communications as the commercial industry realized the potential of using satellites. NASA launched the first Telstar satellite in 1962 and Syncom three, shown in Figure 4, became the first geosynchronous satellite providing television coverage of the Olympics in Tokyo (King and Ricchio 2010).

Successful launches in the 1960s and 1970s of communications satellites added UHF capability with the Submarine Satellite Information Exchange System (SSIXS) (Chief of Naval Operations [CNO] N61 and N87 1998, B-15). Unlike VLF communications which had a slow data rate SSIXS provided a near real time means for tactical and strategic communications. Additional communications circuits were developed by leveraging derivatives of established data management architectures, such as the Battle Group Information Exchange Subsystem (BGIXS) and Officer in Tactical Command Information Exchange System (OTCIXS) to provide direct, bi-directional communications between battle group units and a submarine (CNO N61 and N87 1998, A-34, B-15; Naval Networks Warfare Command [NETWARCOM] 2008).

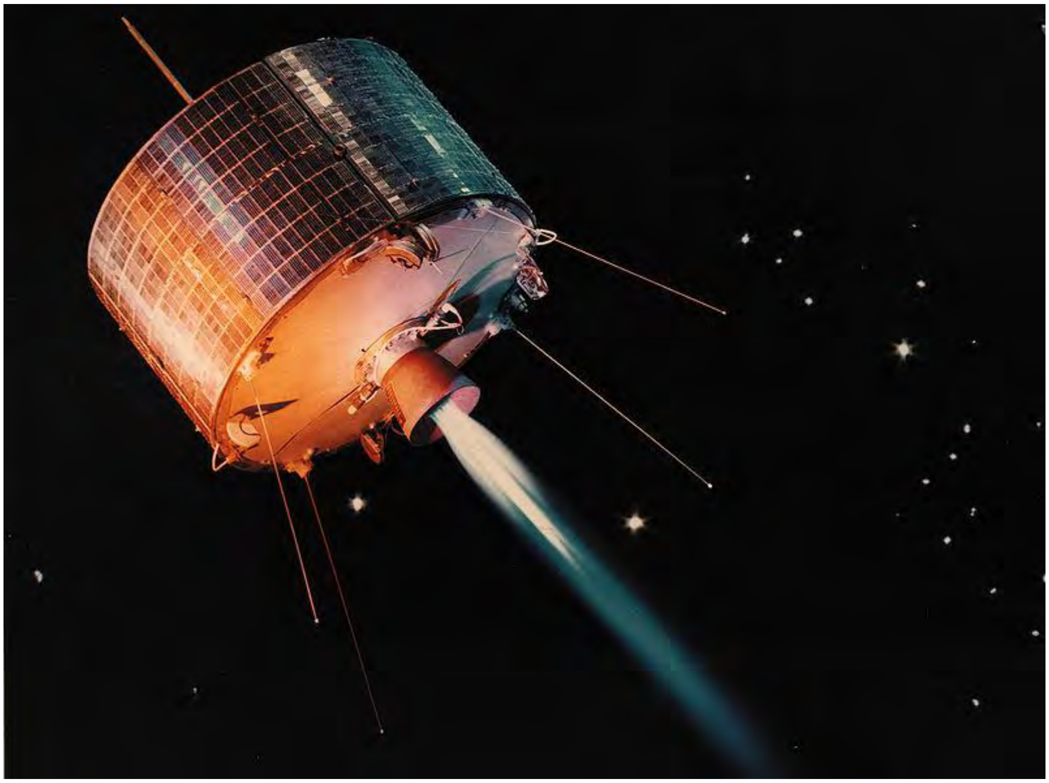

Figure 4. SYNCOM Satellite (from NASA 2009)

These systems were operational well into the first decade of the twenty-first century before being retired. Extremely high frequency (EHF) capable radios were introduced in the 1970s with the Defense Satellite Communications System (DSCS) and expanded to include a larger segment of the RF spectrum. The Military Strategic and Tactical Relay System (MILSTAR) EHF system demonstrated the capability to provide protected communications in a contested environment (King and Ricchio 2010).

Several classes of submarines entered service along with the SSBN. The USS *Permit* class entered service in the early 1960s followed rapidly by the USS *Sturgeon* class. The USS *Los Angeles* (LA) class submarines entered service in 1976 as the replacement for the USS *Sturgeon* class. Originally conceived to be a member of a carrier strike group or battle group there was a greater emphasis on using satellite and LOS communications circuits. The communications capabilities for all of these classes were similar in terms of systems being installed and operated in a stovepipe fashion.

The USS *Ohio* SSBN Trident submarines were the first platforms to deliver an integrated communications capability. The integrated radio room (IRR) was a commercially provided solution based on 1970s technology delivered by the shipbuilder, Electric Boat. Heavily oriented toward reliable communications links the IRR was a contractor delivered system specifically built to support the submarine strategic mission. Designed with a high degree of automation, the IRR was centrally operated by several watch standers responsible to ensure continuous communications in order to act on orders from the NCA received via emergency action messages (EAM). The engineering approach proved the IRR design was robust but its proprietary design proved to be too expensive to maintain and modernize (NUWC 2008, 21). Some minor standalone changes were accomplished in the 1990s to meet the changing technology of Internet Protocol (IP). The last IRR was removed from service in 2011 with the installation of CSRR increment one version one (V1).

The tactical communications system was conceived in the 1980s as an attempt to leverage the Trident centralized control capability to improve nuclear attack submarine (SSN) radio room operability. SSN communications circuits at that time required many steps to lineup, providing opportunities for operator error (NUWC 2008, 15). The USS *Seawolf* (SW) class, designed as follow on to the LA, was planned to use a commercially furnished equipment design similar to the approach of the Trident but also planned to introduce centralized RF and baseband switching. Designed primarily as a Cold War response to the Soviet Navy the significant procurement cost and the end of the Cold War limited the SW procurements to three platforms. Since then they have been modernized with CSRR. The demise of the SW program drove the development of another replacement for the LA class. The new SSN program began development in the early 1990s which ultimately became known as the USS *Virginia*.

In the early 1990s the Navy acknowledged an integrated communication solution was needed. Mission needs statement (MNS) M063-06-95 established the need for an Integrated Maritime Communications System (IMCS) in support of maritime and joint C4I (CNO N81 1995). The MNS outlined the IMCS requirements to encourage improved reliability, survivability, standardization, flexibility, data formats and throughput, use of

commercial-off-the-shelf (COTS), government-off-the-shelf (GOTS) and non-developmental item (NDI) components, provide multi-level security, and reduce life cycle costs. Table 1 lists the objectives for the IMCS and Table 2 outlines the general capabilities from the MNS.

Table 1. IMCS MNS Objectives (after CNO N81 1995)

Integrated Maritime Communications System Objectives		
(1) Improved shipboard information transfer capability by:		
	(a)	Providing reliable and survivable communications connectivity, increased variable information transfer capacity, and timely dissemination in a stressed environment
	(b)	Providing forces with flexibility to rapidly re-align communications service in response to changing operational needs
	(c)	Providing forces with the new information transfer technologies encompassed in personal communications services
(2) Implement improved information transfer capabilities through evolutionary and incremental phasing by:		
	(a)	Standardization of hardware, algorithms, data formats an operational procedures
	(b)	Use of dynamic reprogrammable architecture,
	(c)	Use of open system architecture to ensure delivery of all source SCI information and data
	(d)	Introducing new Non-Developmental Item (NDI) antenna system, (e.g., Pico-cells) to improve survivability and provide user location
(3) Introduce state-of-the-art technology into the information transfer process by:		
	(a)	Shared use of equipment with parallel/redundant capacity and RF links,
	(b)	Maximizing efficiency of resources access control and sub-network processing algorithms
	(c)	Multimedia networking
	(d)	Automation of system control, monitoring, setup, and information dissemination
	(e)	Full use of non-developmental items (NDI), commercial-off-the-shelf (COTS), and government-off-the-shelf (GOTS) applications
(4) Reduce or eliminate the dependence on tethered communications devices without hindering the continued need to disseminate tactical data in near real time within the fleet and from shore to the fleet		

Table 2. Integrated Maritime Communications System General Capabilities (from CNO N81 1995)

IMCS General Capabilities	
1	Decant and direct operational data onto information pathways where operational priorities can be set and managed by doctrine established to manage the system with minimal operator intervention
2	Rapidly reconstitute essential capabilities during degraded modes of operation while maintaining continuity of information. This reconstitution may be accomplished by the use of redundant or reconfigurable equipment
3	Employ data compression, object-oriented transmission packets, "delta" transmission (e.g., sending only the part of data files that actually change between transmission)
4	Accommodate dramatic change in information format characterized generally by voice, video teleconferencing, imaging and digital data, not principally character-oriented textual information
5	Employ more efficient formats, predominantly using binary data files, displayed as high resolution graphics
6	Provide full media capability
7	Perform dynamic bandwidth management using full parallel/redundant networks
8	Provide multi-level security
9	Provide reduced life cycle costs

The submarine communications support system (SCSS) was developed in the 1990s in response to the IMCS MNS (CNO N81 1995) and the release of the original *Submarine Communications Master Plan (SCMP)* (CNO N87 1995). The SCSS began an incremental approach to modernizing the submarine radio room. The FY00 revision to the SCMP (CNO N61 and N87 1998, ii–iii) augmented the MNS requirements as well as defining the phases for the SCSS with the following:

> The SCSS must be a cost-effective system architecture, with emphasis on maximizing commonality between the SCSS suites on all classes of submarines. This comprehensive development and installation plan integrates all current communications improvement programs in a time phased implementation, taking into account the rapid development of communications technology. The defined phases (Automated Message Handling phase (FY94–96), Automated Signal Routing phase (FY97–98), Automated Radio Room phase (FY99–05)) will transition the current radio rooms to a hybrid SCSS, based largely on modern, open systems

architecture (OSA) radios and switching equipment, with some legacy equipment retained.

The SCSS used the submarine message buffer to provide the automated message handling while the submarine baseband circuit switch (SBCS or BBS) and miniature demand assigned multiple access (MINI-DAMA), shown in the land based submarine radio room (LBSRR) in Figure 5, provided the automated baseband, RF switching and improved UHF signal routing using COTS and NDI solutions. Each of these components was still an individual system within the block upgrade approach which packaged capabilities and implemented them within the wideband modernization plan. Packaging these systems enabled them to be integrated, tested and installed as a complete set of capabilities (NUWC 2008).

Figure 5. Submarine Communications Support System Pre-baseband Switch in the Land Based Submarine Radio Room, NUWC Newport (from Keller 2012)

The SCSS was not a formal program, but a concept proving individual component programs could be integrated in order to deliver greater C4I capability. Thus SCSS became the first generation to demonstrate the integration of communications, networking, and automation could meet the MNS objective and capabilities but was limited to the LA class submarines. An online article written by the engineers working for the Naval Undersea Warfare Center (NUWC) Newport and posted by the submarine warfare directorate described SCSS in the following quote

> A key element in this new architecture is the Submarine Communications Support System (SCSS), which adapts Navy-wide communications components and capabilities, while minimizing dependence on submarine-unique equipment. The SCSS will use industry-standard protocols and commercial technology in hardware ruggedized for the rigors of the shipboard environment. Its architecture will phase out today's "stovepipe" systems to implement a client-server environment for exchanging information by means of seamless and comprehensive connectivity on shared, common-user communication links. (Longacre, Exley and Macmillan 1998)

These early radio suites provided a broad spectrum of communications capability and some automation but their stove piped programmatic and technical approaches limited the potential of a more effective and robust C4I system. SCSS and IRR consisted mostly of components unique to the submarine but there was little commonality between their architectures. Sailors transferring from a SSN to a SSBN required extensive retraining prior to reporting. Even within the classes platform configurations would vary greatly. Lack of configuration management and control led to sailors developing their own operating and technical documentation to operate and maintain their radio rooms. IRR maintained tight configuration control but at the expense of not maintaining pace with technology changes in the overall military communications architectures.

The *Submarine Exterior Communications System (SUBECS) Capstone Requirements Document (CRD)* 01-87-98 (CNO N8 1998) provided the specific requirements for the SUBECS. The CRD serves as the operational requirements document (ORD) since the joint capabilities integration development system (JCIDS) process was not yet in existence. The CRD also highlighted the limitations of the current submarine C4I systems. Stovepipe systems, limited throughput, manual operations, and

limited data storage were several of the significant areas of interest. The CRD described the operational capability of the SUBECS to provide attack and fleet ballistic missile submarines with secure, reliable, covert communications, and effectively manage, control, process, and disseminate Command, Control, Communications, Computers and Intelligence (C4I) information (CNO N8 1998).

The SUBECS also had to be interoperable with the global command and control system maritime/ defense information infrastructure-common operating environment (GCCS-M/DII-COE), joint maritime command information system (JMCIS), and joint maritime communications system (JMCOMS). Furthermore, the CRD stipulated the new system must use an open systems architecture approach while still meeting the interoperability requirements. The systems supporting the SUBECS (e.g., SLVR, MINI-DAMA, and BBS) have their own requirements documentation defining key performance parameters for frequency coverage, information routing efficiency, aggregate system throughput, and operational availability (A_o).

Revision one to the CRD (CNO N8 2003) mandated the SUBECS will not develop unique C4I solutions while adding requirements for interoperability with the joint technical architecture standards, joint tactical radio system (JTRS), Navy Marine Corps Intranet and naval integrated information network. SUBECS planned to use a spiral development approach as technology evolved and became available. As a system of systems, the SUBECS leverages other capstone requirements documents to achieve compliance.

The CRD provided the requirements for the Virginia (VA) SUBECS. The FY2000 Director of Operational Test and Evaluation (DOT&E) report described the SUBECS as "an umbrella program, which integrates fifteen smaller acquisition programs and commercial off-the-shelf (COTS) components into a system that supports network centric warfare" (DOT&E 2000, section IV-167). PMS450, the VA program office, originally envisioned implementing an unmanned radio suite capable of automatically managing communications. The manned capability was reinstated at the request of Commander Submarine Forces (COMSUBFOR) due to the observed technology

limitations. The modified version of the SCSS design for the LA class served as the initial plan for the VA.

In the late 1990s, asymmetric communications using submarine Internet Protocol (IP) began fielding as a replacement to the legacy circuits such as SSIXS and OTICXS. The deployment of submarine IP proved to be a complex and lengthy endeavor since engineers had to devise solutions to integrate contemporary and legacy systems. Initially planned as a two year effort in 1998 the full deployment of IP capability to all platforms did not reach FOC until 2007. Even then there were unique solutions for each submarine class. However, the solutions did reflect the initial development of a larger overall open systems architecture.

Commanding officers guidance in revision one of the *Design for Undersea Warfare* (DUSW) (Richardson, Caldwell and Breckenridge 2012) emphasizes the capability to rapidly shift postures from complete communications silence to being fully engaged with other Navy, DOD, or other government agencies to provide support as needed. The DUSW emphasizes a high level, broad requirement for providing systems capable of operating with unmanned aerial or undersea vehicles in a myriad of environments. The commander's guidance lists communications as a key area of proficiency. The DUSW provides additional support to the currently defined requirements for developing an effective SOS capable of meeting the requirements for the submarine warfighter.

The advances of network technology and increasing use of COTS greatly increased the complexity of delivering submarine C4I capabilities. These complexities have proven to be a challenge for acquisition, engineering, and logistics. In many cases the legacy systems had reached their maximum capabilities and were approaching end of life. The next step to address these challenges required considering a new approach. Common Submarine Radio Room was the outcome.

B. COMMON SUBMARINE RADIO ROOM DOCUMENTATION

PMW770 maintains the documentation to support the CSRR program. Using the DOD 5000 series acquisition instructions and memorandums, the required documentation

is created and updated as necessary. Some documents such requirements documents, acquisition plans and strategies remain fairly static once signed. Others such as the test and evaluation master plan and system engineering plan are updated as necessary to support key program events. The SCMP to support the FY2000 program objective memorandum (CNO N61 and N87 1998) is an update to the original SCMP drafted in 1995. It provides a complement to the SUBECS CRD rev one (CNO N8 2003) as well as serving as a compendium of related acquisition requirements. Process documents have been developed to aid in capturing the processes for design, development and testing, and acquisition planning. Information assurance (IA), or Cybersecurity, drives a whole series of documents which captures the relationship of the components of the CSRR.

1. What is Common Submarine Radio Room

CSRR is a network-centric communications system designed to support submarine force C4I requirements. CSRR was designed to provide seamless, transparent, secure connectivity for information exchange between submarines and other joint, naval, DOD, federal, allied and coalition force (PMW770 2008, 9). Figure 6 is the operational view (OV) one (OV-1) from the CSRR capability production document (CPD) (PMW770 2006).

Originally an ACAT III program in 2001 (PMW 173 2002, 5), CSRR became the next step towards a common, modular open systems architecture while expanding automating communications network management. The initial CSRR was based on a VA class submarine contractor furnished design. CSRR was reclassified as an ACAT II program in 2005 (ASN (RDA) 2005) based on the revision to the DOD acquisition guidance which updated the funding levels for development and procurement.

After seeing significant cost increases in the delivery of the first VA CSRR, Program Executive Officer Submarines (PEO SUB) directed an analysis of alternatives (AOA) be performed to determine the optimal acquisition strategy to use. The AOA resulted in the program responsibilities for the lead systems integrator being managed by the government while the original software vendor provided the control and management (C&M) software (PMW173 2002, 18-19).

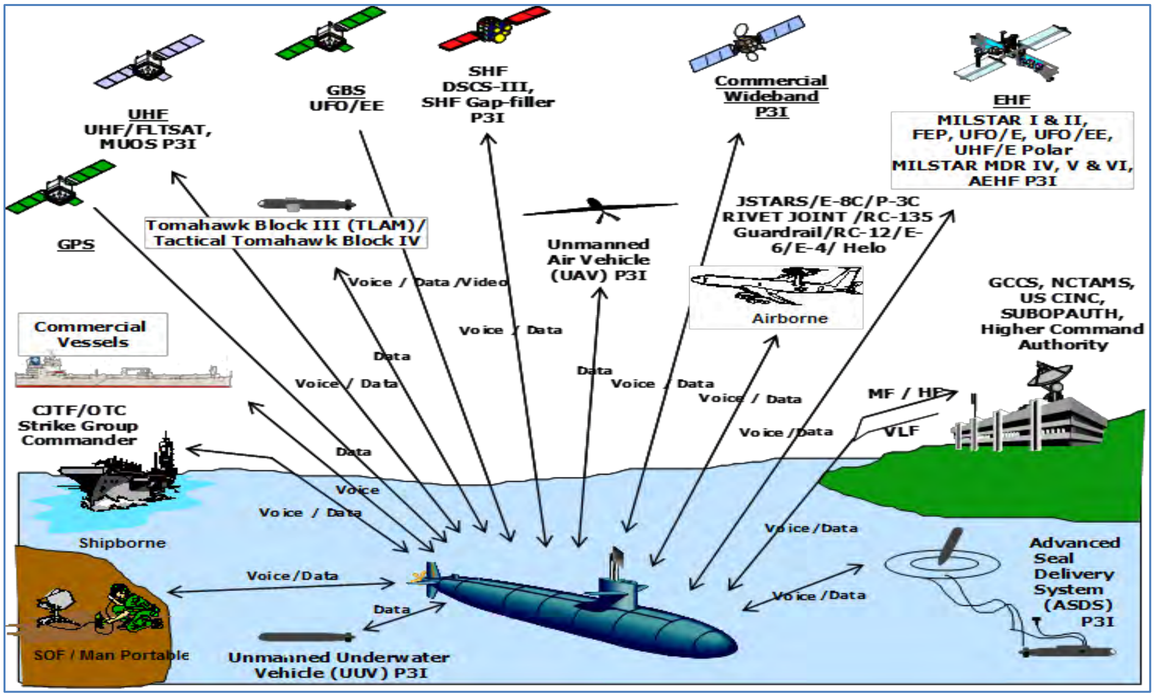

Figure 6. CSRR Operational View (OV-1) (from PMW770 2006, A.1.1)

PMW173 was assigned the responsibilities as the lead systems integrator for the CSRR program. Following the initial delivery for the VA, the approach has been replicated on the SSGN, SSBN and SW classes. Currently, CSRR is deployed in several versions across all classes (e.g., SSBNs have increment one version one (V1), SSGN and SW classes have increment one version two (V2), and VA has increment one versions one, two and three (V3). In 2012 the LA class installed the first CSRR on the USS *Hampton*. The approach has been extended to the Ohio SSBN replacement program (ORP).

CSRR leveraged the benefits of bundling the capabilities of other established acquisition programs of record (POR) and integrating them using an open systems architecture system of systems core design approach. Section 1.3.3 of the CPD (PMW770 2006, 3) provides a general description of the functional end-to-end communications integration. CSRR integrates the program of record component systems, makes any necessary modifications to accommodate any related support equipment and perform coordinated development, testing, and installation of the new capabilities. The design and development is accomplished in a serial fashion, with a version completed for each class before beginning development of the next. The installation of CSRR on the LA platforms

identified the need to evolve this approach in order to preserve operational availability and add flexibility with other PORs.

The baseline system met the submarine exterior communications requirements defined in the CSRR CPD and SUBECS CRD. The *CSRR Systems Engineering Plan* (PMW770 2007) points out CSRR program key performance parameters are dependent on the capabilities of the system that actually makeup a version. Capability upgrades were planned to occur as changes occurred in other programs of record (POR) including automated digital networking system increment three (ADNS Inc3), Navy multi-band terminal (NMT), joint tactical radio system (JTRS), and mobile user objective system (MUOS). Each program maintains its own acquisition responsibilities. CSRR integrates these systems into the overarching architecture, provide updated C&M software, and creates system level documentation and training. These capabilities would fit within the CSRR open system architecture. A sample of the CSRR architecture is shown in Figure 7.

2. CSRR Program Description

The CSRR program is managed by the Undersea Integration Program Office (PMW770) within PEO C4I. PMW770 is the designated lead integrator for systems destined to be installed onboard a submarine or submarine broadcast control authority (BCA). Since a submarine C4I SOS initial capabilities document does not exist for submarine communications the CSRR program must work closely with the other programs in order to achieve the operational requirements identified in the CPD (PMW770 2006, 6).

As an ACAT II program CSRR has the responsibilities as the lead systems integrator. In order to perform this responsibility CSRR is closely engaged with several ACAT I major defense acquisition programs such as the NMT, GBS, MUOS, VA and the Ohio replacement program. The challenge is working with the large and small programs to carry out the duties as the lead systems integrator.

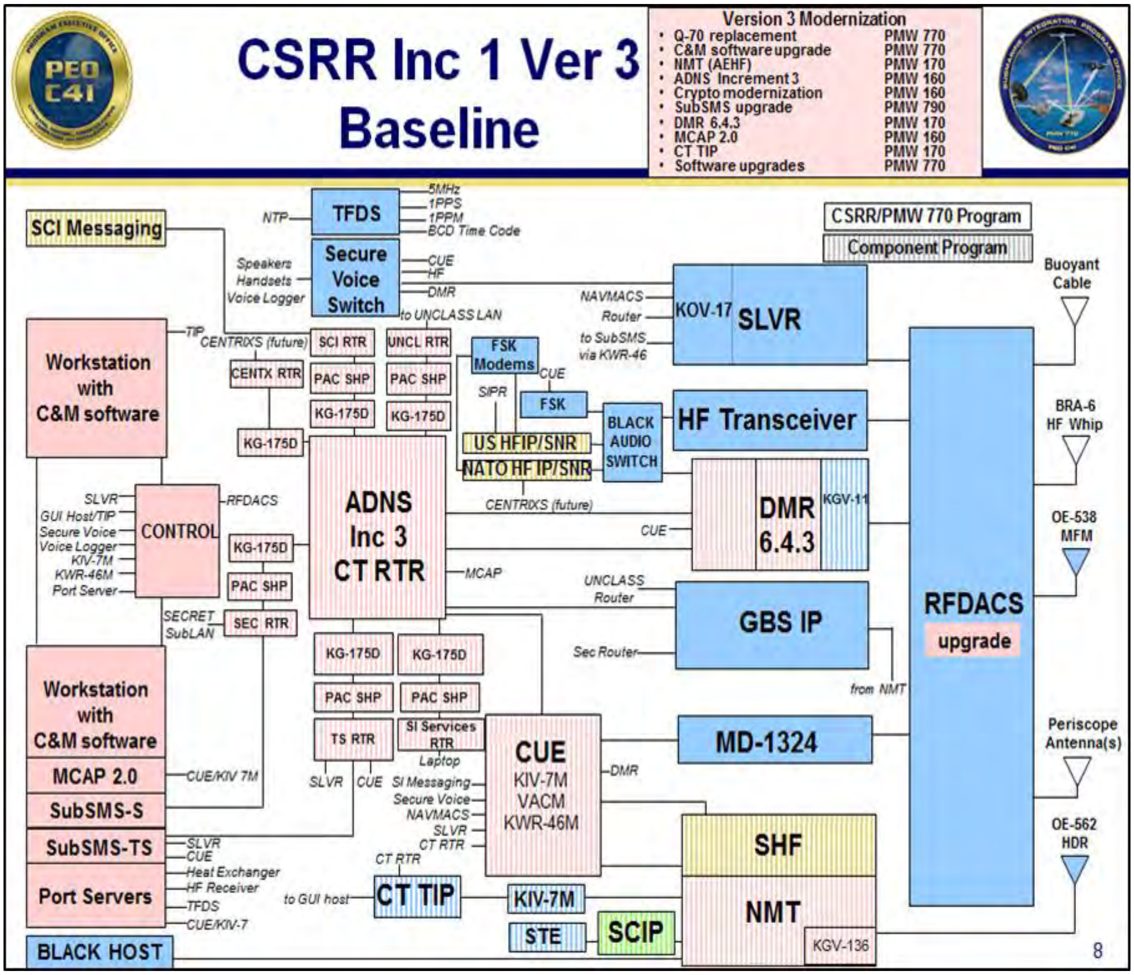

Figure 7. Common Submarine Radio Room (from Anderson 2014)

In this role, CSRR not only integrates systems but coordinates the activities of other organizations and teams. Figure 8 is the organization structure of the Undersea Integration Program Office. The highlighted area is the personnel assigned specifically to the CSRR program. Personnel assigned to the other divisions work closely with the CSRR program and other programs of record (POR) to manage requirements, integration, testing, fielding, and sustainment responsibilities.

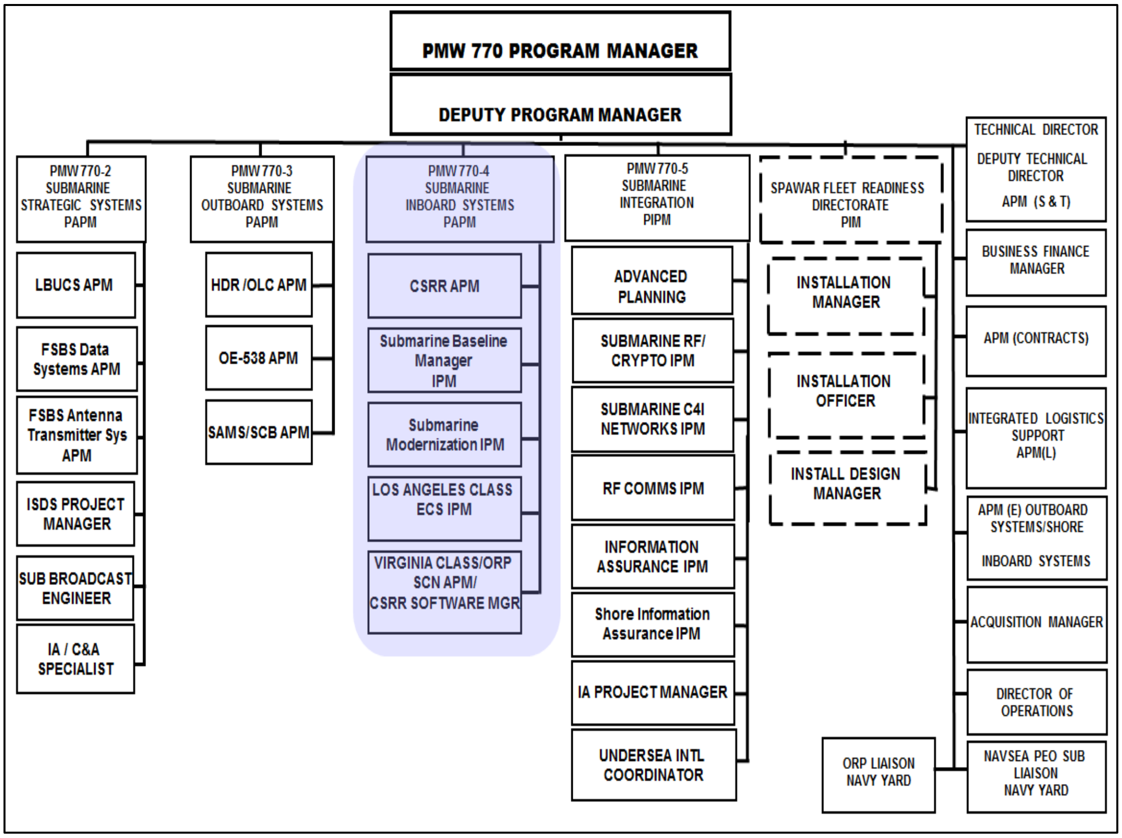

Figure 8. PMW770 Program Office Structure (after Anderson 2014)

The CSRR program team includes a number of external stakeholders responsible for the various functional areas shown in Table 3. These include the OPNAV resource sponsors within the CNO's office, the ships' program managers within Naval Sea Systems Command (NAVSEA), the user community represented by COMSUBFOR, Space and Naval Warfare Systems Command (SPAWAR), SPAWAR Fleet Readiness Directorate (FRD), Space and Naval Warfare Systems Center Atlantic (SSC LANT), Space and Naval Warfare Systems Center Pacific (SSC PAC), Naval Undersea Warfare Center (NUWC) Newport, and Submarine Learning Center. The specific relationships are shown in Table 3. Figure 9 shows the relationships between the internal and external stakeholders supporting the CSRR program. The organizations inside the circle are closely teamed with the CSRR program. This relationship extends into the design and production groups as well the sustainment and training activities in order to develop synergy. Installations are accomplished in a coordinated approach managed by the FRD

through their installation management offices located within SSC LANT and SSC PAC. The SPAWAR/PEO modernization CONOPS (PEO C4I 2005) details how the individual programs and the platform program offices will coordinate their efforts to accomplish design, development and modernization.

Table 3. CSRR Stakeholders

Stakeholder	Relationship
CNO OPNAV N2/N6	Resource sponsor—Provides funding and requirements
NAVSEASYSCOM	Ships Acquisition Platform Manager
COMSPAWARSYSCOM	Functional and matrix support for logistics, systems engineering, and acquisition
SPAWAR Fleet Readiness Directorate	Installation management and sustainment of systems past full rate production
SPAWAR Systems Center Atlantic	Production management; sustainment of in-service systems; training development
SPAWAR Systems Center Pacific	Control and management software development and management
Naval Undersea Warfare Center Division Newport	Design and testing; documentation development
Submarine Learning Center	Training delivery, formal classroom and modernization training
Commander Submarine Forces	End user, requirements generator

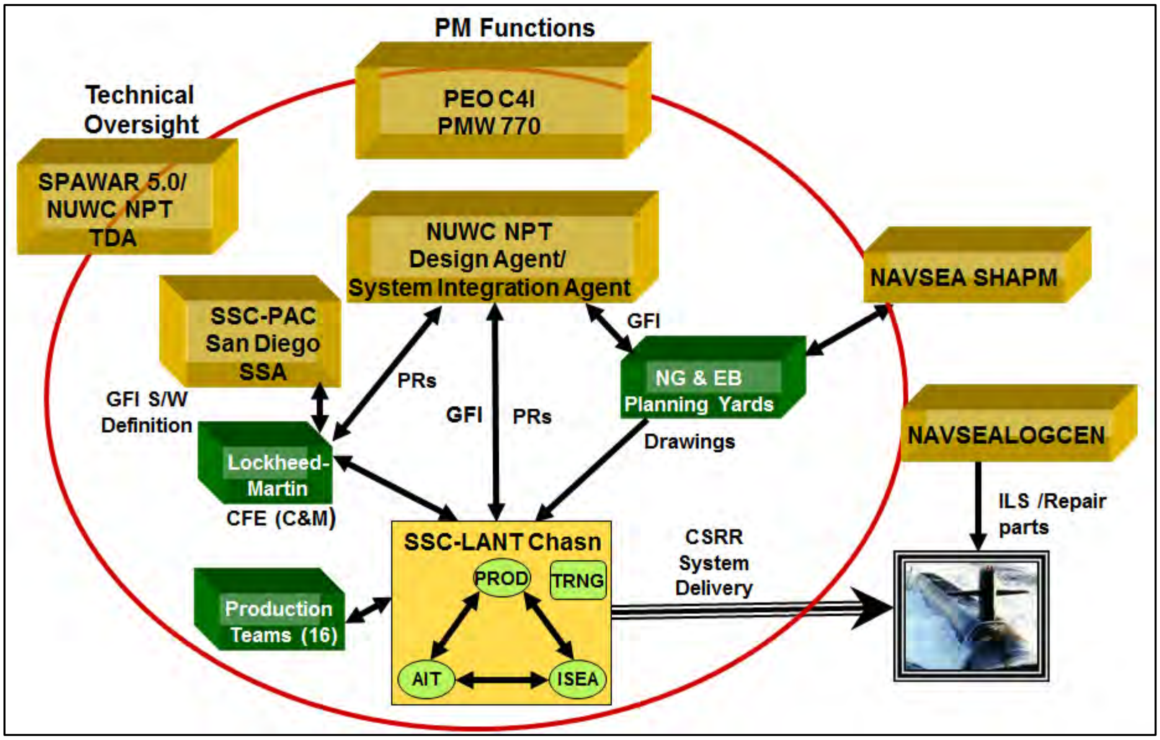

Figure 9. CSRR Program Model (from Anderson 2014)

Revision one of the *Acquisition Plan / Acquisition Strategy (AP/AS)* (PMW770 2008, 13) describes CSRR as a system of systems which integrates Navy PORs. CSRR integrates the systems from other programs of record such as EHF, GBS, ADNS, submarine masts and antennas outboard electronics (OE) OE-538/OE-592, OE-562, periscopes, floating wire antennas, towed buoy antennas, submarine single messaging system (SUBSMS), digital modular radio (DMR) and others. Each system provides an aggregate component, which when integrated creates a system of systems. Each individual system has its own program schedules and required capabilities but when integrated together achieve capabilities not possible as an individual component.

The CSRR test and evaluation master plan (TEMP) (PMW770 2012) discusses all of the testing accomplished previous to V3 and identifies the overarching plan for testing of capabilities delivered with V3. Section 1.3.3 related to key capabilities and interfaces, discusses the necessity of CSRR as a system of systems requirement to interface the component systems, host platform systems, other DOD components, and allied and

coalition partners. The specific performance requirements and characteristics of each component system are defined within their respective program documents.

The CSRR program requirements are defined in the *CSRR Capabilities Production Document* (CPD) (PMW770 2006) and SUBECS CRD (CNO N8 2003). The CPD was developed in support of the production decision for increment one Version zero (V0). The CPD in concert with the CRD, AP/AS, system engineering plan and TEMP outline the main requirements for developing and deploying each successive version of CSRR.

Changing technology presents challenges to system of systems programs since most acquisition documentation is created at the beginning of the program and placed on the shelf after achieving the production and deployment phase. The CSRR circuit matrix (PMW770 2014) is an agreement maintained between PMW770 and the submarine force to capture changes delivered by new programs of record and changes to operational doctrine. The circuit matrix is a living document that is periodically reviewed and updated to reflect the evolving communications capabilities for each CSRR version.

CSRR also identified the need to maintain a common "core capability" (PMW770 2006, 34), which acknowledges there are differences in the submarine platforms but the overall mission requirements remain the same. Maintaining the architecture, workstation and interfaces common across all classes provide the basis for the core capabilities. This same core capability is used in support of the incremental development approach. Once the core capabilities have been identified they form the baseline. This baseline allows for scalability and modularity. This core capability approach was briefed to the milestone decision authority during a gate six review which resulted in maintaining CSRR at increment one with each version providing new capabilities from other programs.

The *CSRR Requirements Design Integration Test Process* (Ross 2013) provides an introduction for new personnel to get acquainted with the CSRR program and for experienced personnel to have a ready reference. The document was generated as a Capability Maturity Model Integration (CMMI) initiative to capture the processes used within the CSRR program management, engineering and test teams.

C. CSRR CONCEPT OF OPERATIONS

A concept of operations (CONOPS) is a vision, verbally or using graphics, of how a system is expected to be employed by the warfighter. The JCIDS (JCS 2012) and Joint Pub (JP) 5-0 (JCS 2011) outlined the purpose of a CONOPS is to illustrate how a joint force commander will organize his forces and deploy them for a particular scenario or in support of the introduction of new capabilities. From the CONOPS the acquisition community can decompose a mission concept into its constituent components and begin defining how to test and deploy once it is ready. The CSRR CONOPS describes the different systems and capabilities available for each version. These capabilities are shown in the various scenarios the submarine would be reasonably expected to execute. There are eight scenarios developed for the CONOPS. Each of these scenarios describes how CSRR will be employed from initial deployment through the post event reporting activities. Figure 10 is a simplified graphic of the systems composing CSRR and its relationship to the external systems.

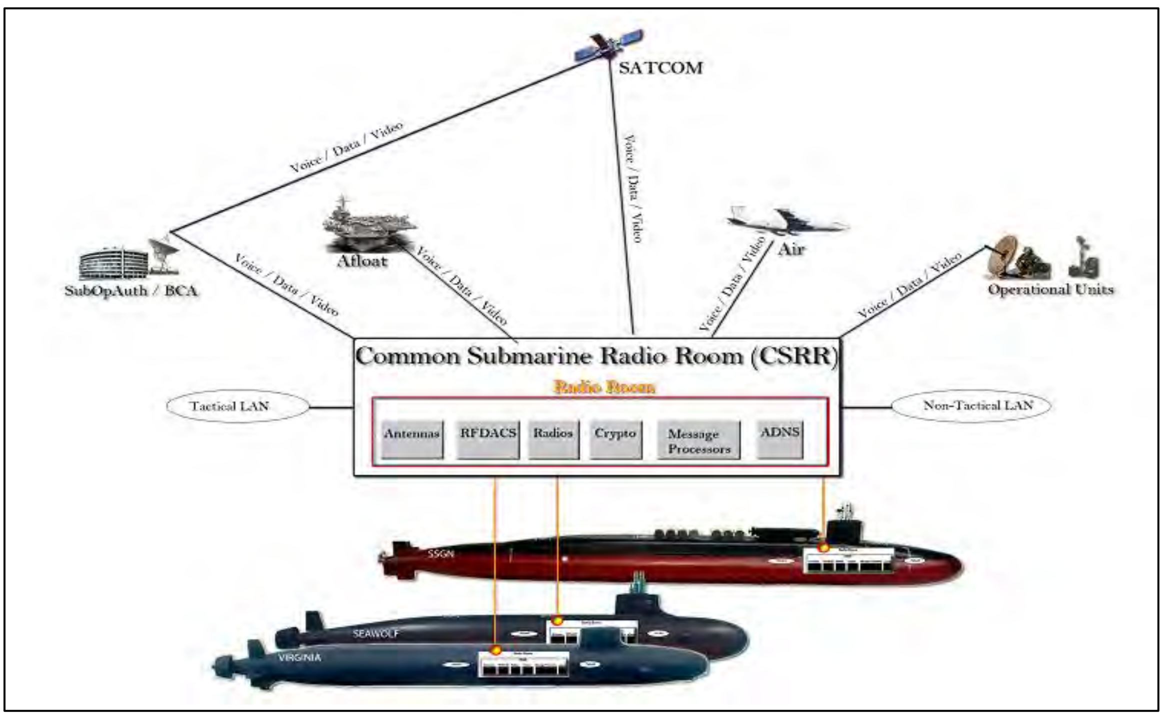

Figure 10. CSRR High Level Concept Graphic (from PMW770 2011b, 2)

Since CSRR is an SOS the CONOPs show the aggregate C4I capabilities needed to support the following mission scenarios:

1. Land attack/strike mission (STK)
2. Intelligence, surveillance and reconnaissance mission (ISR)
3. Carrier strike group/expeditionary strike group operations mission (CSG/ESG)
4. Special operations forces mission (SOF)
5. Mine warfare operations mission (MIW)
6. Undersea warfare mission (USW)
7. Surface warfare mission (SUW)
8. Strategic deterrence mission (SD)

Each mission scenario proceeds through the pre-deployment to post mission reporting. Most scenarios share common pre and post mission activity characteristics but interfaces with different activities and may use different primary and secondary communications paths.

1. Land Attack/Strike Mission

The STK scenario describes the activities that occur in support of launching Tomahawk missiles. The STK CONOPS shown in Figure 11 describes the CSRR activities that occur during each phase by providing the voice, video and data pathways necessary for coordinated land attack/strike operations. Each line identifies the type of communications available in each phase. Data flows are a key element for STK reflected in a majority of the phases.

2. Intelligence, Surveillance and Reconnaissance Mission

Submarines' stealth makes them ideally suited for ISR missions. CSRR enables communications with in-theater, national command, or intelligence community activities to coordinate the entire spectrum of ISR operations during peacetime or hostilities including coordination of STK or SOF missions in hostile areas. More emphasis is on covertness and exchange of intelligence information, including imagery.

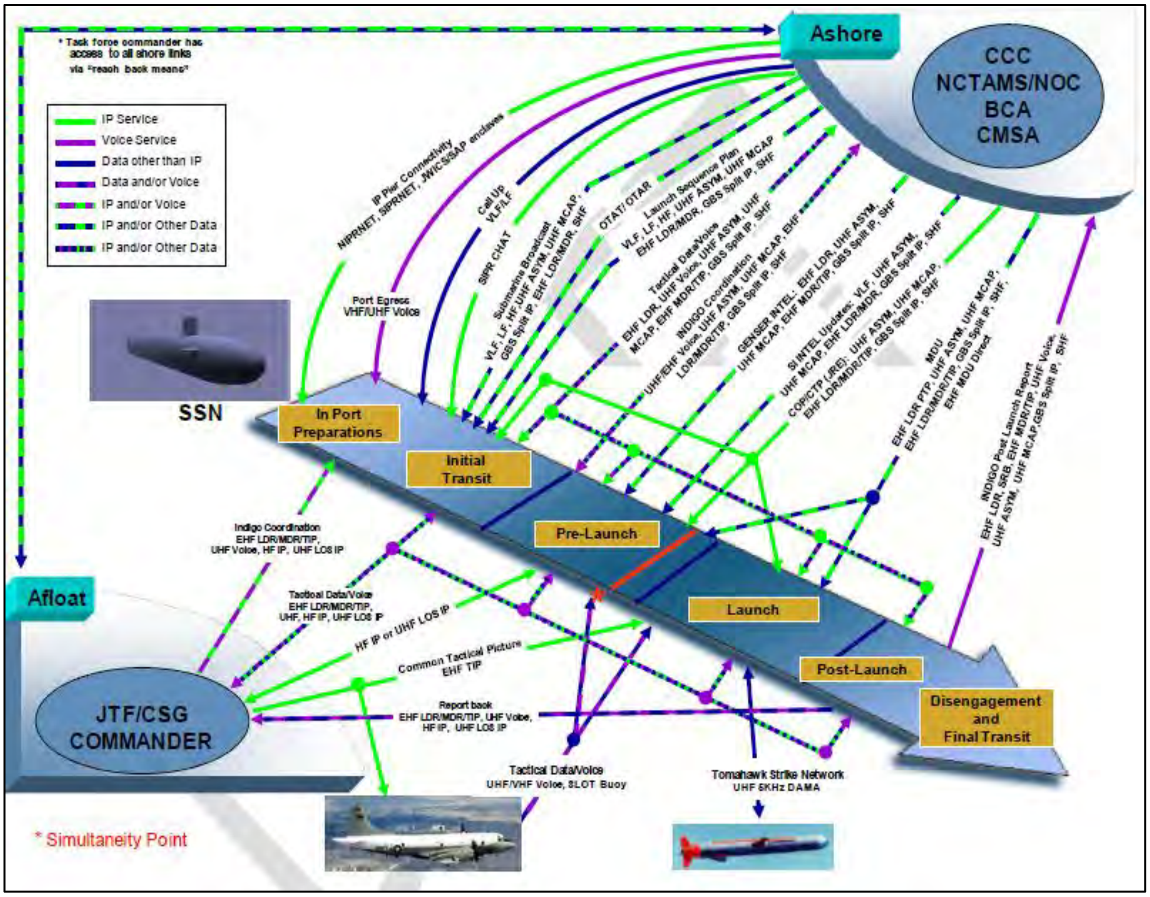

Figure 11. Land Attack/Strike Mission Scenario (from PMW770 2011b, 52)

3. Carrier Strike Group/Expeditionary Strike Group Operations Mission

Attack submarines support CSG/ESG operations. CSRR provides voice, video and data paths for coordinated operations with joint task forces, group and other combatant commanders. This requires the submarine to communicate in a stealthy mode to maximize its search capabilities. More voice circuits are needed in concert with the data flow. Figure 12 shows how a submarine coordinates with the CSG/ESG to provide support adversaries.

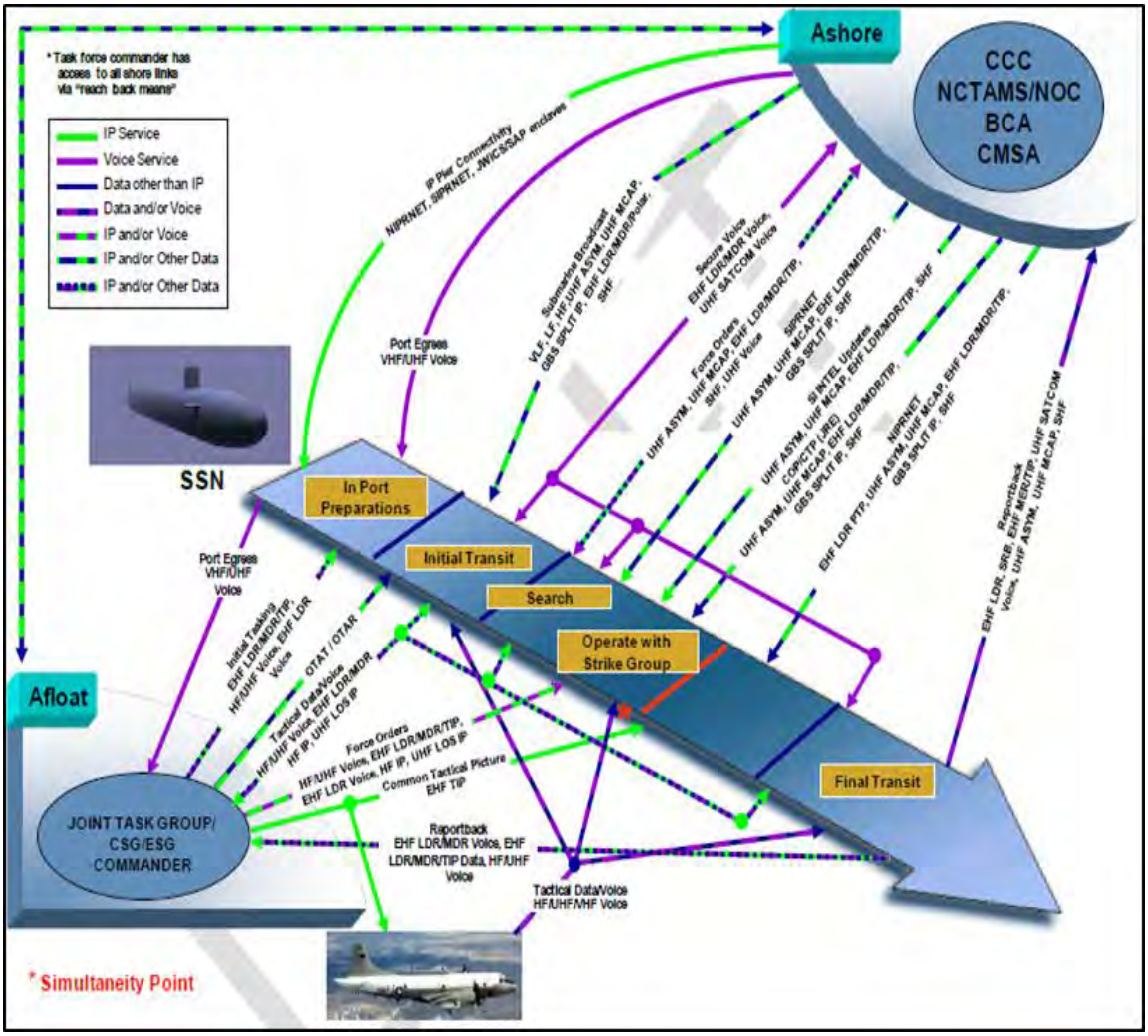

Figure 12. CSG/ESG Mission Scenario (from PMW770 2011b, 67)

4. Special Operations Forces Mission

Submarines are effective platforms for supporting SOF operations for mission planning, insertion, coordination and extraction. Communications emphasizes tactical data and voice circuits required to coordinate with embarked SOF commanders, naval computer and telecommunications area master station, submarine BCA and joint special operations task force.

5. Mine Warfare Operations Mission

Submarines are capable of deploying mines to deny sea areas as well as mapping detected minefields and communicate the information to other units. CSRR supports

execution of this capability through reporting detected minefields. The MIW mission is similar to the CSG/ESG operations mission. The operational nodes and communications paths are the same but data versus voice is sent over the communication lines.

6. Undersea Warfare Mission

USW against hostile submarines is the traditional submarine mission. Typically operating independently, coordination with surface and air units creates a need for common communications during the detection and tracking of enemy submarines. CSRR provides the capability to receive intelligence of detected submarines when in a covert mode or pass intelligence to units assuming the track or prosecution of hostile units. CSRR also provides communications links to support pre-mission operational preparation, common operational picture (COP) updates, situation reports to the USW commander and tasking by the USW Commander. The operational nodes used for the USW mission are the same as the CSG/ESG and MIW missions. The USW mission emphasis is on data paths that support the submarine being deep for extended periods of time, maximizing search effectiveness. USW aircraft also play a significant role in this mission, and therefore they were included as part of the CSG/ESG commander node.

7. Surface Warfare Mission

SUW is a collateral independent mission to track and destroy lone surface units without assistance. However, this opportunity is not available when groups of surface combatants are in the same area. The danger of counter-detection with limited evasion possibilities makes this scenario a cautious one for submarines. If it is not possible for the submarine to conduct a direct attack, then it can assist or coordinate attacks on surface units. CSRR provides communications links to support pre-mission operational preparation, COP updates, situation reports to and tasking from the SUW commander. The operational nodes and data flows are the same as the USW mission. The SUW mission requires greater coordination with other units to prevent engaging friendly contacts and to feed information into the COP.

8. Strategic Deterrence Mission

SSBNs makeup one leg of the nuclear triad remaining submerged to avoid detection while on alert. Reliable communications is a key requirement. Should a missile launch be ordered the SSBN will receive their orders via an emergency action message (EAM). Common Submarine Radio Room receives intelligence, situation reports, and EAMs while operating in a covert manner. Additionally, CSRR supports communications links for pre-mission operational preparation, COP updates, targeting change messages (TCM), situation reports and tasking. Figure 13 depicts the nuclear command, control and communications (NC3) infrastructure needed for mission communications while performing a strategic deterrent patrol. The BCA provides the interface to the NC3 system for delivery of EAMs. Take charge and move out (TACAMO) aircraft and surface ships relay EAMs if there is a failure of the primary reception paths. The simultaneity point indicates when multiple communications paths will be available for use.

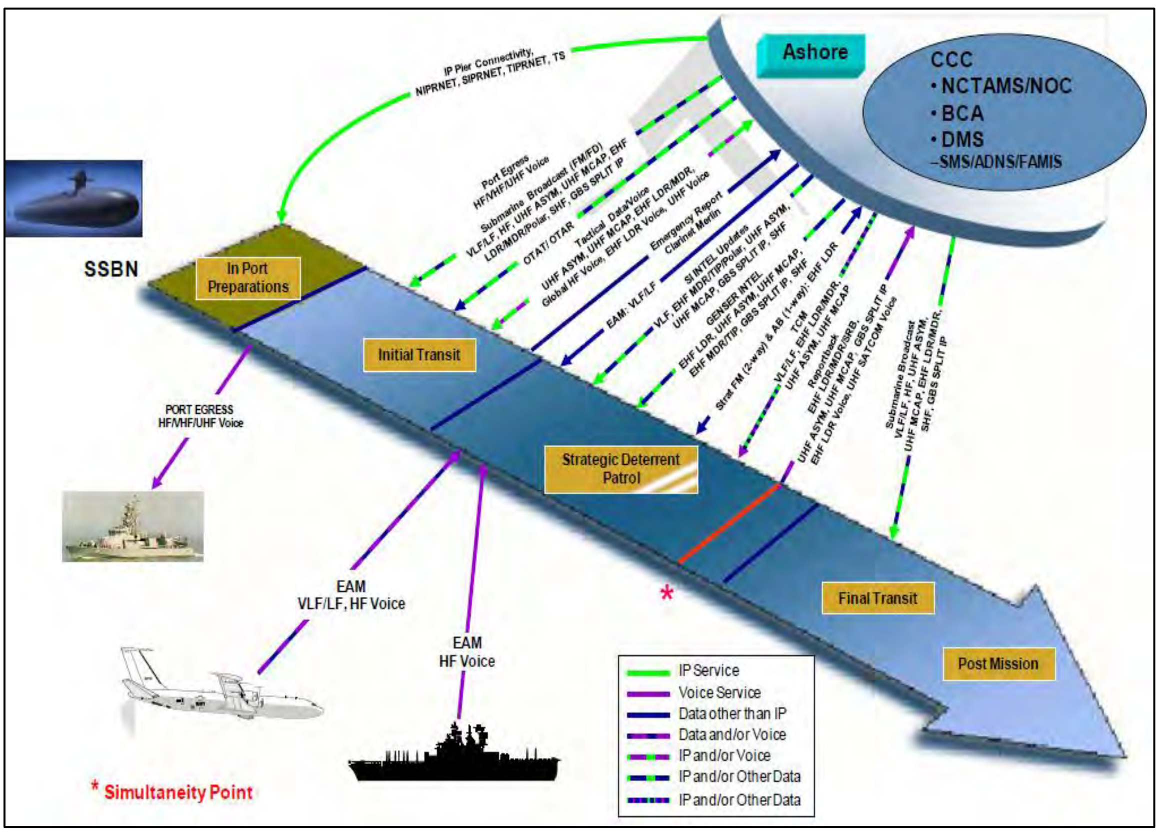

Figure 13. Strategic Deterrence Mission Scenario (from PMW770 2011b, 106)

D. SYSTEMS COMPRISING CSRR

Section 2.4 of the revised *CSRR Acquisition Strategy / Acquisition Plan* (AS/AP) (PMW770 2008) defines CSRR as a network-centric communications system of systems, integrating several program of record systems within a common architecture to provide secure, reliable, and covert communications and effectively manage, control, process and disseminate command, control, computers, intelligence, surveillance and reconnaissance (C4ISR) information. Systems engineering activities during the development phase address issues to align the individual system requirements with the CSRR SOS requirements. The program office continually engages with the PORs to integrate and deploy new and updated capabilities in an evolutionary manner. CSRR is composed of systems from the following program offices as shown in Figure 14.

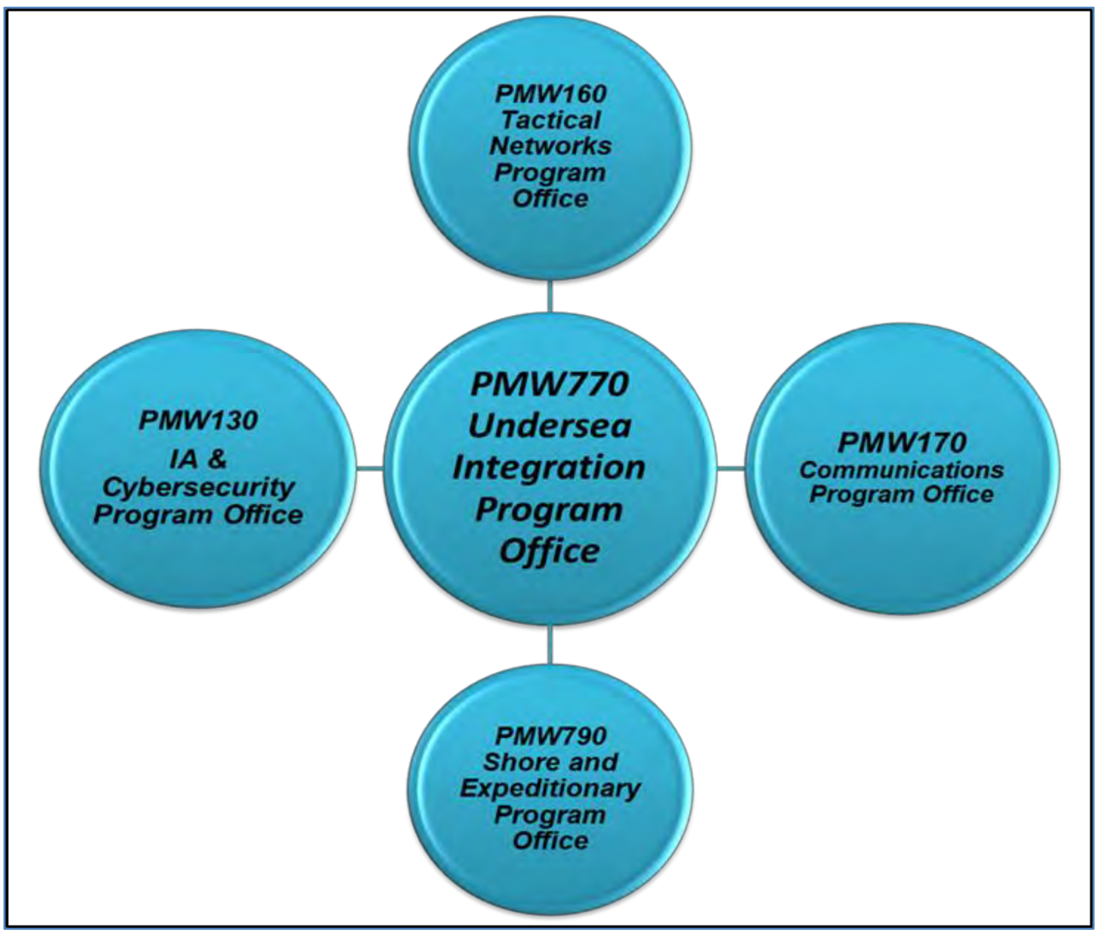

Figure 14. CSRR Program Relationships to Other Programs of Record

The CSRR program shares product development and integration responsibilities. Within this scope CSRR integrates the individual component systems procured via their parent program offices, shown in Figure 15, and procures or modifies subsystem components and ancillary equipment (e.g., racks, rack cabling, and routers) into a common, open architecture baseline, with control and management of the physical components provided by the CSRR C&M software. The AS/AP directs how CSRR program must approach the modernization of each version for considering technology insertion activities to integrate new products and capabilities.

> The open system architecture maximizes the use of COTS, allows for the rapid insertion of technology, and addresses emerging requirements and/or obsolescence issues. This design flexibility is particularly important in this submarine communication program due to changing requirements and emerging technical advances.
>
> Use of non-proprietary standards and protocols enhance the program's ability to efficiently and effectively respond to requirements changes, incorporate commercial system improvements, and improve interoperability within the GIG.
>
> The CSRR modernization plan will continue to apply open system architecture concepts and plans for platforms with technology refresh back fits concurrent with modernization increments. (PMW770 2008, 26)

Baseline updates are closely managed and accomplished as minor upgrades or in concert with a larger version modernization effort. Updates include C&M software changes incorporating new functionality or capability. The Gate Six review (PMW770 2008, 1-2) authorized a change to the AS/AP defining version vice increment upgrades. The significance of this decision eliminated the requirements to create new acquisition documentation but did direct each version to accomplish operational testing (OT). The extent of testing is negotiated with Director, Operational Test and Evaluation (DOT&E), and Commander, Operational Test and Evaluation Force.

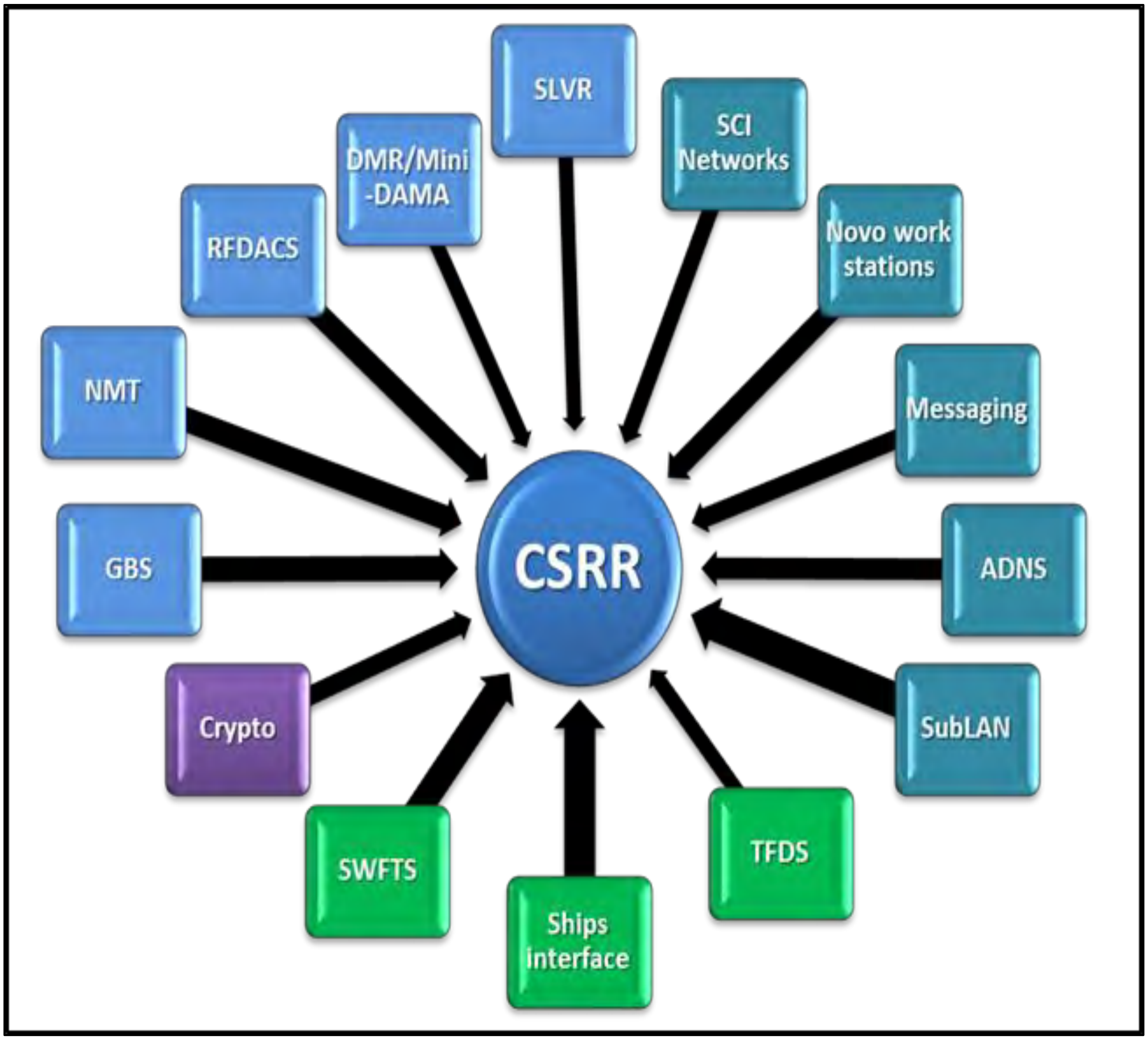

Figure 15. Programs of Record Systems Composing CSRR

Testing accomplished by individual programs of record will be leveraged where possible, however the main intent is determine if CSRR as a system of systems still meets requirements and is deemed operationally effective and suitable. The following program offices provide their products for integration and testing into a CSRR version.

1. PMW 130 Information Assurance and Cybersecurity Program Office

PMW 130 provides cyber security products and services and cryptographic products to protect Navy and Marine Corps C4I systems (PEO C4I 2012). PMW 130 provides the following systems.

a. Crypto Universal Enclosure

The crypto universal enclosure (CUE) provides a common host for the various modern crypto devices.

b. Electronic Key Management System

The electronic key management system (EKMS) handles the administrative and key generation capabilities onboard the platform.

c. Cryptographic Devices

There are a number of cryptographic devices required to support secure communications across the various communications and IP networks. Most of these devices are hosted in the CUE.

2. PMW 160 Tactical Networks Program Office

PMW 160 manages the network programs for afloat, airborne, and ashore nodes (PEO C4I 2012). These include the Automated Digital Networking System (ADNS), Sensitive Compartmented Information (SCI) and Special Intelligence (SI) Network System, and Submarine Local Area Network (SUBLAN).

a. Automated Digital Network System

The Automated Digital Network System (ADNS) is an ACAT III program managed within the Tactical Networks Program Office and provides the main access point to the Navy tactical / strategic and global information grid resources and services. ADNS provides wide area network (WAN) connectivity and is the Navy's bandwidth optimization program of record to provide quality of service routing for voice, video and data using the available communications links within the ship / shore WAN. ADNS interfaces to the various Navy networks to enable interfaces to U.S. classified and unclassified networks, and Allied and Coalition networks (General Dynamics 2008).

b. Sensitive Compartmented Information Networks

The primary mission of sensitive compartmented information (SCI) networks provides connectivity to the intelligence community to provide shipboard analysts with access to national and service strategic and tactical databases. SCI networks is the transport medium providing special intelligence data and secure WAN IP access to ship and shore national Web sites, signals intelligence and intelligence databases for seamless interaction between shore, surface, submarine and airborne special intelligence LANs (PEO C4I 2012).

c. Submarine Local Area Network

Submarine Local Area Network (SUBLAN) is a reliable high-speed secret, sensitive but unclassified and top secret local area network (PEO C4I 2012). When the SUBLAN network is combined with other subsystems, it provides the shipboard network services and uses CSRR as the gateway for off hull services to deliver an end-to-end net centric warfare capability. The Consolidated Afloat Network Enterprise System (CANES) is the next generation network planned for afloat units to consolidate many of the individual networks into a larger system of systems network (PEO C4I 2014).

3. PMW/A 170 Communications and Navigation Program Office

PMW/A 170 provides satellite, line-of-sight, and extended-line-of-site communication systems for voice and data communications and Global Positioning System (GPS) capabilities for ship navigation, command and control systems and weapons systems (PEO C4I 2012). PMW 170 oversees the Navy EHF satellite program, DMR, Global Broadcast Service (GBS), Time Division Multiple Access Interface Processor (TIP), and Portable Radio Program.

a. Military Strategic and Tactical Relay System / Navy Extremely High Frequency Program / Navy Multiband Terminal

The military strategic and tactical relay system (MILSTAR) EHF system was introduced in the 1980s as an answer to the challenges facing users of the UHF band to provide tactical and strategic communications in all environments. Bandwidth capability

has grown since its introduction from 2400 bps to over 24 Mbps. The Navy Multiband Terminal (NMT) is the latest maritime military satellite communications terminal supporting the Military Satellite Communication (MILSATCOM) architecture to provide connectivity in all domains. NMT supports the advanced extremely high frequency program for protected satellite communications. The NMT communicates via the Wideband Global Satellites and Defense Satellite Communications System (DSCS) for super high frequency (SHF). NMT operates over EHF low data rate, medium data rate, and extended data rate communication modes (PEO C4I 2012).

b. Global Broadcast Service

Global Broadcast Service is a joint program led by the Air Force to provide high bandwidth capability to deliver classified and unclassified products. Classified as an ACAT 1 program, GBS leverages the EHF system as a transport for a “smart push” and “user pull” approach for delivering products. Data can include full motion video, imagery, maps, orders, and weather information. Unified commanders manage the flow of these products over the portions of the system supporting their area of responsibility. GBS uses CSRR and ADNS to route information to the classified and unclassified computers. Live video feeds are sent to the submarines training and entertainment system for viewing by the crew (CNO N61 and N87 1998, 3-13).

c. Digital Modular Radio

Digital Modular Radio is a multi-channel software programmable radio capable of operating across the HF-UHF frequency spectrum and is interoperable and compatible with legacy systems (PEO C4I 2012; General Dynamics 2014). The DMR is the COTS replacement for the MINI-DAMA.

d. Miniature Demand Assign Multiple Access

The MINI-DAMA is a legacy two-channel VHF/UHF radio retained in the LA class CSRR Increment 1 V3. Built in the 1990s, the MINI-DAMA provides UHF SATCOM and LOS capability and incorporates the Advanced Digital Waveform (ADW)

to support the Medium Data Rate Channel Access Protocol (MCAP) circuit (Federation of American Scientists [FAS] 1999).

e. MD-1324 Advanced Digital Waveform Modem

Early versions of DMR do not have the ADW waveform integrated as an organic capability. In order to support improved throughout the MIL standard for UHF waveforms was updated to include ADW. The MD-1324 has the ADW waveform to support MCAP by interfacing the modem with the DMR power amplifiers.

f. PSC-5D Integrated Waveform Radio

The integrated waveform (IW) was developed by the Defense Information Systems Agency as a solution to diminishing UHF resources. The PSC-5D is a commercial radio installed on LA platforms to provide IW capability.

4. PMW770 Undersea Integration Program Office

PMW770 is responsible for the development, acquisition, and integration and fielding of systems planned for the undersea domain (PEO C4I 2012). They manage product and integration responsibilities for the following programs: Radio Frequency Distribution and Control System (RFDACS), Q-70 and Novo workstations, control and management (C&M) software, SLVR, OE-538 Multifunction Mast, OE-562 Submarine High Data Rate (SUBHDR), BRR-6 towed buoy antenna and OE-315 floating wire antenna.

a. Radio Frequency Distribution and Control System

The RFDACS provides an automated interface between the radios and submarine antenna systems, amplifying and distributing RF frequencies to various systems such as GPS.

b. Q-70 and Novo CSRR Workstations

The workstations provide the human-machine interface between the operator and CSRR. The C&M software provides the graphical user interface to align and operate the various communications circuits available to the operator.

c. RT-9000 HF Transceiver

The RT-9000 is a COTS radio installed on LA class submarines. The radio provides HF voice and data capability.

d. CSRR Ancillary Equipment

Ancillary equipment consists of HF modems, secure voice switch, black audio switch,

e. Submarine LF/VLF Versa Module Eurobus Receiver

SLVR is the VLF/LF receiver capable of receiving and processing all Navy, special, and NATO modes. SLVR receives message traffic from the FSBS via one of several VLF antennas while submerged. The SLVR is installed on all submarines and is operated from the CSRR operator work station. SSBNs have additional capability to directly control the SLVR via a local processor and can send messages directly to a printer for handling (CNO N61 and N87 1998).

f. Time and Frequency Distribution System

The TFDS provides precision time and frequency information to communications, electronic warfare, periscope, navigation, combat, and ship control systems aboard attack and Trident class submarines. The TFDS is a NDI system using two rubidium standards which eliminate single points of failure. The TFDS can select inputs from the internal standards or an external device such as GPS. The TFDS provides a variety of outputs for frequency and timing and time code. The TFDS originated as a Submarine Integration Program Office as an ACAT IVT program. In 2011 the FRD assumed sustainment responsibilities.

g. OE-538 Multi-Function Mast Antenna Group

The OE-538 antenna group is an improved, multifunctional, combined communications, navigation and Identification Friend or Foe (IFF) mast-mounted antenna system for all submarine classes. The OE-538 covers the RF spectrum for all VLF to UHF requirements including IFF and GPS and provides significant reliability improvements (CNO N61 and N87 1998). Increment 2 expands the capability to include support for the Mobile Users Objective System (MUOS), iridium, and Tactical Data Link via Link 16.

h. Submarine High Data Rate Antenna System

The SUBHDR antenna provides connectivity for the EHF, SHF and GBS communications for submarines capable of supporting data rates up to eight megabits per second. The SUBHDR antenna uses a 16-inch dish antenna which is controlled by the EHF terminal to point the satellite.

5. PMW 790 Shore and Expeditionary Systems Program Office

PMW 790 manages the Navy's messaging systems to provide the message handling and distribution responsibilities for afloat and shore activities (PEO C4I 2012). Within PMW 790 is the submarine single messaging system (SUBSMS) which is composed of the following:

a. Navy Modular Automated Communications System II

The Navy modular automated communications system model (NAVMACS) II is a ship to ship, ship to shore messaging system which handles organizational message traffic and routes it to the ships LAN for distribution to the appropriate mailbox. In event a high priority message is received it can be configured to print out a copy for immediate action. NAVMACS is set up primarily to handle incoming serial traffic transmitted by the FSBS or MILSTAR (NUWC 2012, 194-196).

b. Submarine Single Messaging System Support Server

The SUBSMS support server (SSS) is the main system to send and receive organizational message traffic received over an IP broadcast. The SUBSMS interfaces with the NAVMACS II to manage message reception, processing, storage and transmission (NUWC 2012, 194–196). Additionally, SUBSMS hosts the Information Screening and Delivery System which handles messages received via IP paths and routes them to the various users on the SUBLAN.

6. Activities External to PEO C4I

CSRR interfaces with multiple systems managed by other program offices within PEO SUB and Program Executive Office Integrated Warfare Systems (PEO IWS) under NAVSEA, Nuclear Command and Control under Strategic Systems Programs (SSP), strike and airborne relay via Naval Air Systems Command (NAVAIR), and submarine force sponsored installations and alterations.

a. Program Executive Office Submarines

PEO SUB manages the submarine warfare federated tactical system (SWFTS). SWFTS, shown in Figure 16, is an SOS model composed of the combat control, sensors, SUBLAN, shown in yellow, and CSRR managed under a mutual agreement between the systems commands. CSRR, shown in pink, is considered a system within this larger SOS. These systems are managed within NAVSEA under PEO SUB and PEO IWS and program management air (PMA) 271 under NAVAIR. NAVSEA has responsibility as the ship acquisition program manager for oversight of all submarines acquired and currently in service.

b. Strategic Systems Programs

Strategic Systems Programs has oversight of all NC3 systems. CSRR interfaces with the NC3 community through SSP and their agent Naval Surface Warfare Center Dahlgren to certify messaging paths responsible for delivery of nuclear command and control information.

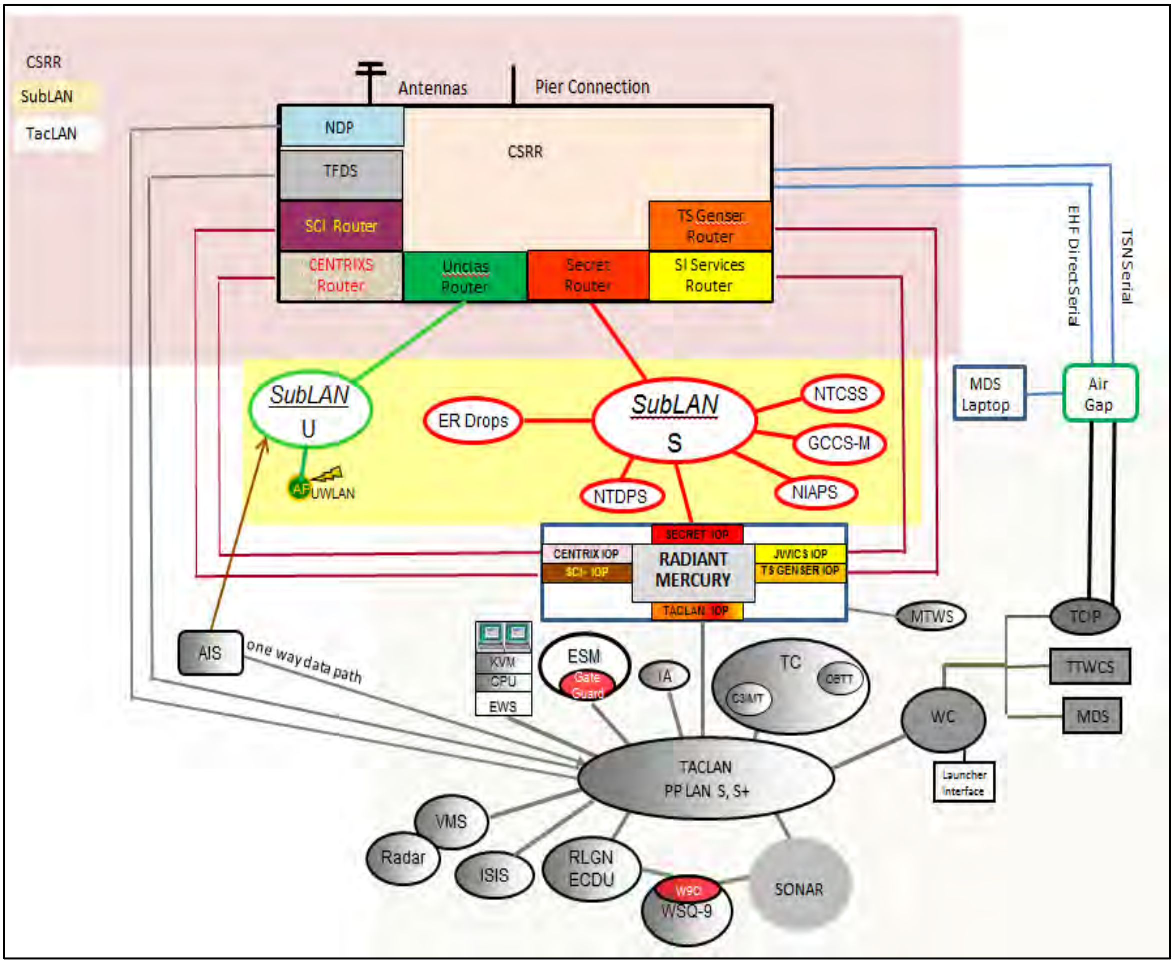

Figure 16. Submarine Warfare Federated Tactical System (after PMW770 2012b)

E. SYSTEMS ENGINEERING AND SYSTEM OF SYSTEMS ENGINEERING PRINCIPLES

DOD continuously develops and procures systems to support the warfighter. These systems must meet their requirements in terms of cost, schedule, and performance. Sound systems engineering (SE) is critical to design, deliver, and support complex system of systems in order to achieve these key tenets. The number of attempts to institute acquisition reform during the last 30 years has proven challenging with few substantial changes really occurring. The Weapons Systems Acquisition Reform Act of 2009 provided several changes to include mandating use of SE and establishing the

Deputy Assistant Secretary of Defense for Systems Engineering (DASD SE). The Government Accounting Office annual high risk report (GAO 2013, 151) reported the following

> Moving forward, DOD faces challenges in extending the influence of the Weapons Systems Acquisition Reform Act. These challenges include: limited organizational capacity to support cost estimating, performance assessment, systems engineering, and developmental testing; lack of guidance in certain areas; limited dissemination of lessons learned related to systematic problems and best practices; and differences between the Office of the Secretary of Defense and the military services about what constitutes an appropriate level of risk and whether the benefits of certain reform provisions are worth the cost

As systems become more complex and rely more heavily on COTS this task becomes more difficult. The challenge of systems engineering (SE) and system of systems engineering (SOSE) is clearly articulating the terminology in the context of each. Systems engineers may opine SOSE is merely an extension of SE but SOSE practitioners will point out there are key differences. For example application of the SE process includes clearly defining system requirements at the beginning of a program. A SOSE engineer will most likely be looking at systems which already have established requirements. Understanding the differences in approach is critical during each phase for developing a system of systems such as CSRR. This section looks at the meaning of systems, system of systems, systems engineering, and system of systems engineering in order to provide a common understanding.

1. Systems

A system is defined by INCOSE as "an integrated set of elements, subsystems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements" (Haskins 2014). The *Systems Engineering Book of Knowledge (SEBOK) v1.3* (Adcock 2014) defines a system as "a set of elements and a set of inter-relationships between the elements such that they form a bounded whole relative to the elements around them." Furthermore, the SEBOK v1.3 refers to Bertalanffy's (Adcock 2014) discussion of systems within his general systems theory as

General system theory (GST), attempts to formulate principles relevant to all open systems. GST is based on the idea that correspondence relationships (homologies) exist between systems from different disciplines. Thus, knowledge about one system should allow us to reason about other systems.

Other definitions include the Defense Systems Management College's (DSMC) (2001) view "Simply stated, a system is an integrated composite of people, products, and processes that provide a capability to satisfy a stated need or objective."

The *NASA System Engineering Guide* (2007, 3) provides a slightly different if more technical view of a system in the following quote

> A construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce system-level results. The results include system-level qualities, properties, characteristics, functions, behavior, and performance.

The formation of the components or elements to create a useful product is visible in almost everything we see, hear, or touch. Nature itself has systems (e.g. the ecosystem) which is made up of a set of elements to create a forest, or desert or reef.

2. System of Systems

There is a great deal of disagreement over what is the definition of a system of systems (SOS). One of the generally accepted definitions has been defined by INCOSE. According to INCOSE (Adcock 2014) defines a SOS as

> systems-of-interest whose elements are themselves systems; typically these entail large-scale inter-disciplinary problems involving multiple, heterogeneous, distributed systems. These interoperating collections of component systems usually produce results unachievable by the individual systems alone

The Assistant Secretary of the Navy for Research, Development and Acquisition (ASN (RDA)) released a supplemental guide *Systems of Systems Engineering Guidebook Version 2.0* (2006) defining system of systems as an

> integrated force package of interoperable systems acting as a single system to achieve a mission capability. Typical characteristics include a high degree of collaboration and coordination, flexible addition or removal of component systems, and a net-centric architecture. Individual systems within the SOS may be capable of independent operations and are typically independently managed

The Under Secretary of Defense for Acquisition, Technology and Logistics (USD (AT&L)) (Director Systems and Software Engineering 2008) defined a system of systems as

> a set or arrangement of systems that results when independent, and task-oriented systems are integrated into a larger systems construct, that delivers unique capabilities and functions in support of missions that cannot be achieved by individual systems alone

Jamshidi (2009), in his opening chapter section 1.2, outlines six definitions of system of systems from other researchers (Jamshidi 2009, 3). These are listed in Table 4 below and illustrate the wide disparity in determining what a SOS is and what it should be able to do.

Table 4. System of Systems Definitions (from Jamshidi 2009, 3)

1.	Enterprise system of systems engineering (SOSE) is focused on coupling traditional systems engineering activities with enterprise activities of strategic planning and investment analysis [Carlock and Fenton, 2001].
2.	System-of-systems integration is a method to pursue development, integration, interoperability, and optimization of systems to enhance performance in future battlefield scenarios [Pei, 2000]. [Luskasik, 1998].
3.	Systems of systems exist when there is a presence of a majority of the following five characteristics: operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development [Jamshidi, 2005].
4.	Systems of systems are large-scale concurrent and distributed systems that are comprised of complex systems [Jamshidi, 2005; Carlock and Fenton, 2001].
5.	In relation to joint war-fighting, system of systems is concerned with interoperability and synergism of Command, Control, Computers, Communications, and Information (C4I) and Intelligence, Surveillance, and Reconnaissance (ISR) Systems [Manthorpe, 1996].
6.	SOSE involves the integration of systems into systems of systems that ultimately contribute to evolution of the social infrastructure [Luskasik, 1998]

The following quote is Jamshidi's definition of a system of systems

> systems of systems are large-scale integrated systems which are heterogeneous and independently operable on their own, but are networked together for a common goal. The goal, as mentioned before, may be cost, performance, robustness, etc. (2009, 4)

Vaneman and Budka (2013, 2) identified a system of systems as "SOS as a system of all platforms, assets, systems, nodes, and networks that join together to achieve a capability needed to conduct a mission." These definitions would be applicable to many systems within the DOD inventory.

The contrast of this however is discussed by Dahmann, Rebovich and Lane (2008) that many of the systems within DOD were created as standalone systems, failing to benefit from the consideration of how they will fit in the overall defense architecture. Table 5 identifies the differences between a system and a system of systems. Systems engineers and SOS engineers must work to synchronize their efforts in order to meet the requirements for cost, schedule, and performance for each.

In the context of command and control Manthorpe (1996, 305–310) stated "Linking systems into joint system of systems allows for the interoperability and synergism of Command, Control, Computers, Communications, and Information (C4I) and Intelligence, Surveillance and Reconnaissance (ISR) System." Systems with joint requirements such as the Global Command and Control System-Maritime (GCCS-M) are becoming increasingly interlinked in terms of requirements, development and acquisition. Their ability to operate only with similar systems within their networks prevents effective employment of information supporting the user. The increasing complexity and use of networks to support war fighting has made the requirement to develop systems that work together increasingly visible. The holistic view provided by a SOS approach provides a more clearly defined role of how a system will fit in the overall SOS architecture. In summary a SOS capability is greater than the sum total of the individual components.

Table 5. Comparison of Systems and System of Systems (from Dahmann, Rebovich and Lane 2008, 5)

Aspect of Environment	System	Acknowledged SoS
Management and Oversight		
Stakeholder Involvement	Clearer set of stakeholders.	Stakeholders at both system level and SoS levels (including the system owners, with competing interests and priorities); in some cases, the system stakeholder has no vested interest in the SoS; all stakeholders may not be recognized.
Governance	Aligned project manager and funding.	Added levels of complexity due to management and funding for both the SoS and individual systems; SoS does not have authority over all the systems.
Operational Environment		
Operational Focus	Designed and developed to meet operational objectives.	Called upon to meet a set of operational objectives using systems whose objectives may or may not align with the SoS objectives.
Implementation		
Acquisition	Aligned to acquisition categories milestones, documented requirements, SE with a SE plan.	Added complexity due to multiple system lifecycles across acquisition programs, involving legacy systems, developmental systems, new developments, and technology insertion; typically have stated capability objectives up front which may need to be translated into formal requirements.
Test and Evaluation	Test and evaluation of the system is generally possible.	Testing is more challenging due to the difficulty of synchronizing across multiple systems' life cycles, given the complexity of all the moving parts and potential for unintended consequences.
Engineering and Design Considerations		
Boundaries and Interfaces	Focuses on boundaries and interfaces for the single system.	Focus on identifying the systems that contribute to the SoS objectives and enabling the flow of data, control, and functionality across the SoS while balancing needs of the systems.
Performance and Behavior	Performance of the system to meet specified objectives.	Performance across the SoS that satisfies SoS user capability needs while balancing needs of the systems.

Systems of systems are classified as one of four types (Director, Systems and Software Engineering 2008; ASN (RDA) 2006; Vaneman & Budka 2013, 3): virtual, collaborative, acknowledged and directed. The type of SOS to be used can be planned from the beginning (directed) such as an entire architecture such as the littoral combat ship (LCS), ORP, or GPS. A virtual SOS is an ad hoc grouping of systems into a largely cooperative effort. A good example may be the organization of units in response to an emergency. A collaborative SOS example is the local internet service provider or the Defense Acquisition Community Connection Communities of Practice. The acknowledged SOS is the most common form seen across DOD. This can be seen when a cooperative agreement exists between individual participants and the lead systems integrator role. Each type is described in Table 6.

Table 6. System of Systems Types (from Director, Systems and Software Engineering 2008, 4-5)

Types of System of Systems	Description
Virtual	A virtual SOS is essentially an ad hoc group of systems. There is no single authority or agreed upon purpose. Large scale behavior emerges and may be desirable. But this type of SOS must rely upon invisible mechanisms to maintain it.
Collaborative	Component systems interact more or less voluntarily to fulfill agreed upon central purposes. Stakeholders work collectively to provide some means to enforce and maintain standards (such as interface standards).
Acknowledged	There are recognized objectives, a designated manager, and resources for the SOS. Constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches. Changes in the systems are based on collaboration between the SOS and the system. A lead systems integrator may be an acknowledged SOS.
Directed	The integrated system-of-systems is built and managed to fulfill specific purposes. It is centrally managed during long-term operation to continue to fulfill those purposes as well as any new ones the system owners might wish to address. The component systems maintain an ability to operate independently, but their normal operational mode is subordinated to the central managed purpose. An example of this would the USS *Virginia* submarine program. The platform is made up of numerous smaller systems and system of systems.

A SOS in contrast to a system, however complex, will evolve over time as functions, components, and requirements change for the individual systems (Jamshidi 2009). Managing a SOS presents additional challenges due to the nature of the evolution, or fuzziness of future requirements. The SOS engineer not only must consider the individual systems capabilities and requirements but must arrange all of the components in an optimal manner to achieve operational synergy.

Redundancy within a SOS is a factor which can separate it from a system. Redundancy can have different meanings but typically becomes a question of the risk of failure versus the consequences of failure. Traditional and sociotechnical systems can be categorized as Type I or Type II (Jamshidi 2009, 199). Type I SOS have redundancy built

in; if one system should fail the others are capable of reconfiguring or rerouting to continue operations. Type II SOS have no such redundancy.

Resilience is another characteristic of a SOS. Jackson and Ferris (2013) outlined in their paper the principles of resilience in an engineered system. Using the definition recognized by the U.S. government resilience is "the ability to adapt to changing conditions and prepare for, withstand, and rapidly recover from disruption" (Jackson and Ferris 2013, 153). They go into further detail to break down this definition and define the 14 principles for resilience.

3. Systems Engineering

Systems engineering (SE) dates back to the 1940s to the Bell laboratories. The actual usage of SE principles dates earlier to the 1900s (Buede 2000, 6). Engineers and scientists were applying the principles within their own specialties but as they crossed with other fields new rules for developing and managing a system were required. An early example of systems engineering would be a locomotive. Whereas a formal requirements review probably did not occur the information still had to be defined. The use of SE identified key factors such as size, speed, range and cost.

INCOSE defines SE as "an interdisciplinary approach and means to enable the realization of successful systems" (Haskins 2012, 7). According to the SEBOK (Adcock 2014) SE

> focuses on holistically and concurrently understanding stakeholder needs; exploring opportunities; documenting requirements; and synthesizing, verifying, validating, and evolving solutions while considering the complete problem, from system concept exploration through system disposal

SE is supported by technical and technical management processes to enable focusing on successful development, delivery, and sustainment of a system meeting the customer's needs while considering business and technical needs involved (Haskins 2012). The *NASA Systems Engineering Handbook* (NASA 2007, 3) provides a more holistic view:

> Systems engineering is the art and science of developing an operable system capable of meeting requirements within often opposed constraints. Systems engineering is a holistic, integrative discipline, wherein the contributions of structural engineers, electrical engineers, mechanism designers, power engineers, human factors engineers, and many more disciplines are evaluated and balanced, one against another, to produce a coherent whole that is not dominated by the perspective of a single discipline

SE processes within various organizations share many common traits. A study funded by the Under Secretary of Defense for Acquisition, Technology and Logistics (USD (AT&L)) (Patterson, Dubin, and Richter 2004) evaluated the SE activities performed by each service, civilian government agencies, associations, the models available and education opportunities. Understanding these activities provides a common framework for effective use of SE processes and principles used by many programs and projects.

4. System of Systems Engineering

Using Wikipedia as a starting point, system of systems engineering (SOSE) is a set of developing processes, tools, and methods for designing, re-designing and deploying solutions to system-of-systems challenges (*Wikipedia* 2013). DOD develops many complex systems which require using SOSE approaches. A more scholarly definition defines "SOSE involves the integration of systems into systems of systems that ultimately contribute to evolution of the social infrastructure (Luskasik 1998 quoted in Jamshidi 2009, 3). The *Defense Acquisition Guidebook* (DAG) (Defense Acquisition University [DAU] 2008) defines SOSE as "a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities." The USD (AT&L) developed their initial version of the *"Systems Engineering Guide for System of Systems"* (Director, Software and Systems Engineering 2006) and ran a pilot to evaluate 18 programs within DOD. They found the following:

1. Systems of systems tend to be continual efforts addressing user needs through a combination of systems.
2. Systems of systems typically are not new acquisition programs.
3. Program managers of a system of systems usually do not have requirements or funding for the individual systems.

4. System of systems capabilities evolve over time.
5. A well designed system of systems is more capable of incorporating incremental upgrades.

USD (AT&L) directed an update to its *Systems Engineering Guide for System of Systems (USD SOSE Guide)* V.9 to V1.0 recognizing the value SOSE has in enabling the development of complex systems in today's environment. The *USD SOSE Guide* defines SOSE as "planning, analyzing, organizing, and integrating the capabilities of a mix of existing and new systems into an SOS capability greater than the sum of the capabilities of the constituent part" (Director, Systems and Software Engineering 2008). Additionally USD (AT&L) recognized SOSE must consider a variety of systems whether they are fully developed, or in an as yet to be defined state(Director, Systems and Software Engineering 2008) .

The challenge of SOSE varies due to the level of complexity involved. This can vary from spontaneous, short-lived, simple SOS to long lived, complex, and continuously evolving SOS (Jamshidi 2009). Examples of a simple, ad hoc SOS may be a planned response to a casualty or disaster. In this case each individual system (e.g., the police, fire, paramedics, utilities, and other groups) each provide a component for responding to the event. Individually, they are still capable of accomplishing their primary role, but collectively they comprise a larger capability (e.g., responding to a mass casualty). A more complex example defined by Jamshidi (2009, 15) is a "galactic SOS" which is represented by an ecosystem or a community. Jamshidi continues by stating these complex SOS are characterized with

> an open systems approach to create a healthy, dynamic architecture, enabling them to effectively capitalize on open systems development principles and strategies such as modular design, standardized interfaces, emergence, natural selection, conservation, synergism, symbiosis, homeostasis, and self-organization (Jamshidi 2009, 16)

An additional challenge to SOSE is the lead engineer must routinely integrate existing systems. Since they do not control the requirements, boundaries and development, the end result can be suboptimal. External environmental effects further complicate issues for the lead engineer. The complexity of engineering a SOS using the

trapeze model can be improved through implementing a wave model (Dahmann et al. 2011). The colored blocks shown of the trapeze model in Figure 17 represent the different activities and how they are related to each other. The activities move from translating objectives to assessing performance and understanding the systems to evolving the SOS architecture. For example attempting to orchestrate upgrades requires the SOS engineer understand how the systems are interrelated, what the capability objectives are in terms of the individual systems and the overarching SOS. The arrows between the SOS engineering activities swing back and forth like a trapeze. This in turn drives how to assess the performance impacts of the proposed upgrades. The drawback of the trapeze model is the sequence of activities is not clearly defined and hard to follow.

The sequence of events within the trapeze model can be transformed by "unwrapping" the process and correlating the processes to the wave model. The colored blocks are aligned on the left within a swim lane to show where they would occur. Converting to a wave model provides a better detail of the activities and their sequence (Dahmann et al, 2011). Figure 18 illustrates the unwrapping and final results as a wave model. The unwrapped wave model provides a much clearer picture of the order of the activities for analysis, development and implementation.

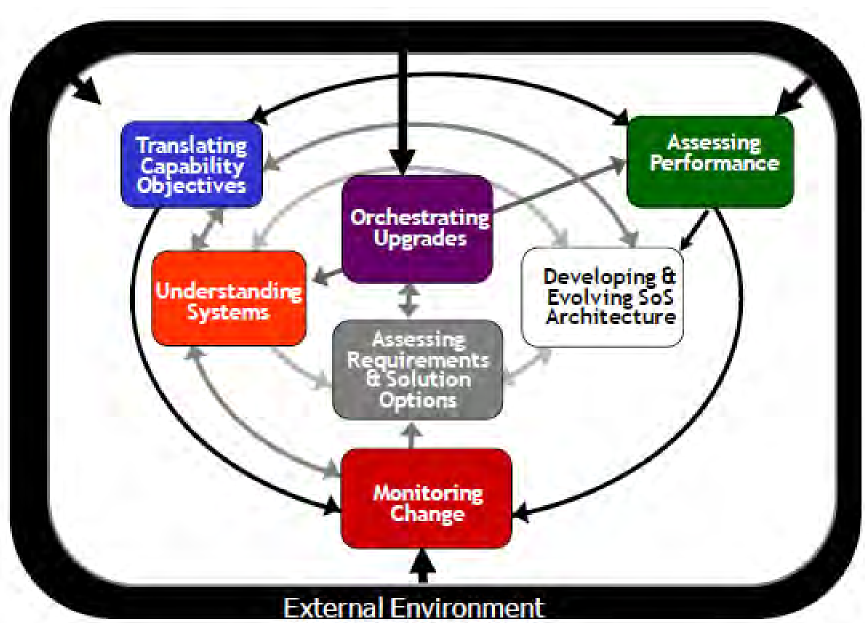

Figure 17. Trapeze Model (from Dahmann et al 2011, 2)

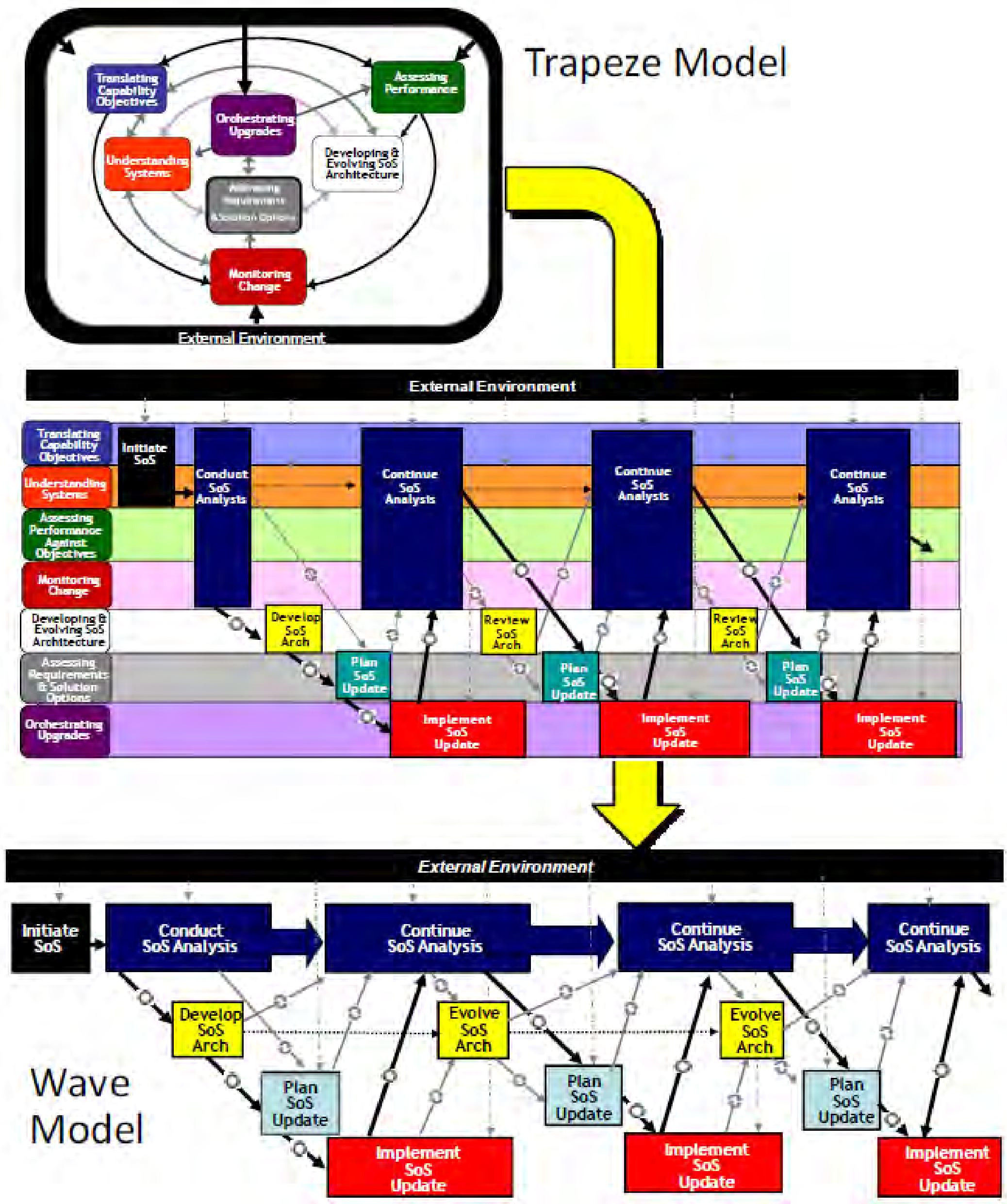

Figure 18. Unwrapping the Trapeze Model into the Wave Model (from Dahmann et al 2011, 3)

Another factor challenging SOSE is the lack of a standardized language. Thousands of standards are developed by hundreds of organizations which contribute to the confusion when discussing SOSE and comparing one against another. These standards and their application can be derived into a concept of "universally agreed-upon set of guidelines for interoperability" (Jamshidi 2009, 457). The guidelines define the

following levels of standardization: compatibility, interchangeability, commonality, and reference. From an SOS perspective these levels create "compatibility, similarity, measurement, and symbol and ontological standardization" (Johnson 2009, 457). As SOS development evolves and matures standards among the various disciplines will be created. Johnson (2009, 461) emphasizes without a common language a SOS cannot communicate with other SOSs, will not be fully functional, and is not capable of allowing new components to be added without significant effort.

A system of systems needs a means of governance. Governance encompasses all of the processes to create and manage an organization regardless if it is formal or informal. Effective governance will define the activities that need to occur, identify who has authority to accomplish those actions and verify they are being accomplished. Without effective governance, similar to a lack of effective C2, the risks of delays or failure increase greatly. Challenges to successful SOS governance were identified by a study performed by the Center for Public Policy and Private Enterprise (Gansler, Lucyshyn and Rigilano 2012, viii). Five categories were identified which can affect successful SOS governance: leadership, management, requirements, human resources and funding (Gansler, Lucyshyn and Rigilano ix–xiii). Berteau et al (2013, 646) presented eight attributes for the acquisition governance of a SOS using the future combat system (FCS) and maritime domain awareness programs (MDA) as case studies shown in Figure 19. The Software Engineering Institute performed a study on system of systems attributes to define the characteristics of effective governance. They identified six characteristics concerning collaboration, accountability, evolution, and processes (Morris, Place and Smith 2006).

The Deputy Assistant Secretary of the Navy for Research, Development, Testing and Evaluation (DASN(RDT&E) Chief Engineer and SPAWAR Information Technology Technical Authority (ITTA) identified five SOS qualities necessary for good governance (Vaneman and Jaskot 2013). Table 7 describes the characteristics of the directed and virtual SOS with collaborative and acknowledged SOS somewhere in between. Application of these principles provides a framework amenable to managing the activities surrounding system of systems development and sustainment.

GOVERNANCE ATTRIBUTE	DESCRIPTION
LEVEL OF ORGANIZATIONAL FOCUS	The level at which SoS governance occurs within the organization. This is not the same as systems/capabilities focus or technical focus, both of which are outside the scope of the CSIS SoS governance analysis.
INTEGRATION OF FUNCTIONAL END-USER NEEDS	The mechanism(s) and frequency with which the functional needs of end-users are built into the system-of-systems, and at which points in the process of delivering the system-of-systems this incorporation occurs.
DECISION-MAKING AUTHORITY	The formal mechanism by which delivery of systems-of-systems is governed, including how budget is allocated, standards are set, tradeoffs are managed, and inconsistencies are adjudicated.
ENFORCEMENT	The mechanisms and level of management oversight by which the objectives of the SoS capability to be delivered are ensured, including measurements and program metrics.
WORKFORCE	The examination of SoS workforce structures, unity of mission, and capability development and enhancement through use of contracted support.
INCENTIVE STRUCTURE	The alignment between enterprise goals and the incentive and reward structures of the components that implement them.
KNOWLEDGE OWNERSHIP / ACCESS TO KNOWLEDGE	The accessibility of information regarding the operating environment, technical standards, and other elements that comprise the system-of-systems.
RISK ASSESSMENT / RISK MANAGEMENT	Risk assessments and management strategies tailored to mission accomplishment and the flexibility and resilience required for delivering systems-of-systems in the face of unforeseen developments.

Figure 19. Attributes of Acquisition Governance (from Berteau et al 2013, 14)

Testing and evaluation of a SOS involves taking a broader, more holistic perspective. Brooks and Sage (2005/2006, 268) pointed out while SOS integration is a complex affair the ability to accomplish validation and verification are just as important. The FY2000 DOT&E (2000, section IV-170) annual report pointed out several important points regarding testing in terms of challenges and benefits.

1. Shorter acquisition cycles due to accelerations to field technology would make testing more challenging.
2. The use of COTS should be tempered with the risks to degrading training, logistics, and documentation.
3. Effective use of the requirements and testing strategy can keep the program focused on the goal.

Table 7. System of System Characteristics (from Vaneman and Jaskot 2013)

Characteristics	Definition	Directed SOS	Virtual SOS
Autonomy	The ability to make independent choices; the right to pursue reasons for being and fulfilling purposes through behaviors	Conformance: Autonomy is ceded by parts in order to grant autonomy to the system	Independence: Autonomy is exercised by constituent system in the order to fulfill the purpose of the SOS.
Belonging	To be a member of a group; to have the proper qualifications	Centralize: To bring under one control; to come together to form a center.	Decentralization: Constituent systems choose to belong on a cost/benefit basis, also in order to cause greater fulfillment of their own purposes, and because of belief in the SOS supra purpose.
Connectivity	The ability of a system to link with other systems.	Platform-centric-Prescient design, along with parts, with high-connectivity among sub-systems.	Network-centric; Dynamically supplied by constituent systems with every possibility of myriad connections between constituent systems, possible via a network-centric architecture to enhance SOS capability.
Diversity	Noticeable heterogeneity, having distinct or unlike elements or qualities in a group; the variation of social and cultural identities among people existing together in an operational setting.	Homogeneous: Managed, that is, reduced or minimized by modular hierarchy; parts diversity encapsulated to create a known discrete module whose nature is to project simplicity into the next level of hierarchy.	Heterogeneous: Increased diversity in SOS capability achieved by released autonomy, committed belonging, and open connectivity.

Characteristics	Definition	Directed SOS	Virtual SOS
Emergence	The appearance of new properties in the course of development or evaluation.	Foreseen: Foreseen, both good and bad behavior, and designed in or tested out as appropriate.	Indeterminable: Enhanced by deliberately not being foreseen, though its crucial importance is, and by creating and emergence capability climate, that will support early detection and elimination of bad behaviors.

F. CASE STUDIES

Case studies provide the opportunity to capture a teachable moment, learning principle, a lesson learned, and share the results with others. Case studies are an effective means to train engineering and acquisition professionals about real systems in use today (Soy 1997; Bahill and Chapman 1994, 145). Stjelja (2013, 3) made the following comment about case studies "An important aim of the case study approach is to capture the complexity of a single case." Additionally Stjelja continues "Case studies, thus, cannot be defined through its research methods but rather through an interest in what is to be studied, and given the definition above it should be noted that a case study is not a method but a research strategy (Stjelja 2013, 3).

A case study can take a number of approaches. Soy (1997) uses a methodology with six steps from defining the questions to completing the final report. Bahill and Chapman (1994) outline a commercial approach of benefits versus efforts. The Friedman and Sage framework (2003, 88–96) shown in Figure 20 and Table 8 analyzes nine areas and stratifies responsibilities by contractor, government, and shared responsibilities.

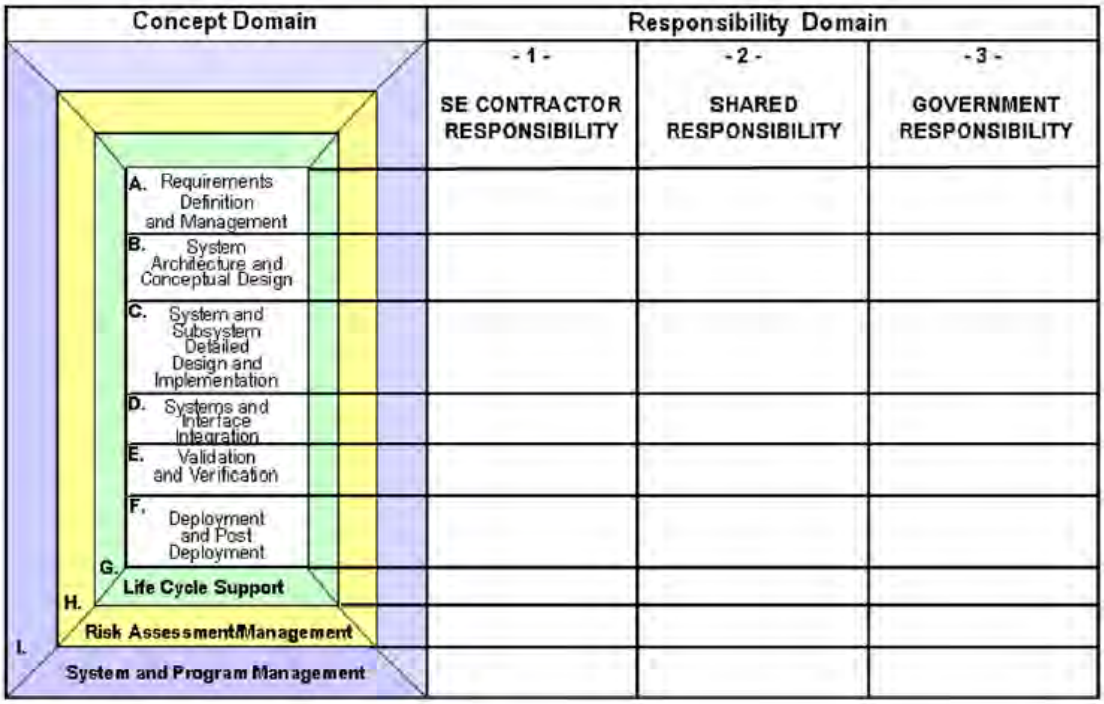

Figure 20. Friedman and Sage Framework (from Friedman and Sage 2003, 88)

Table 8. Description of the Friedman and Sage Framework Domains (after Friedman and Sage 2003, 89–96)

		A	B	C
	Integration approach	Prime contractor is responsible for SOSE	Govt acts as integrator and program manager	Govt contracts out individual components and the SOSE responsibilities
A	**Requirements definition and management**	Requirements shall flow downward in a coherent and traceable manner from the top level to all lower levels	Customer and contractor shall share their knowledge of the technical maturity relative to new, unprecedented systems being engineered	Govt shall integrate the needs of its user organizations woth he management activities of its engineering organizations
B	**Systems architecture development**	The system baseline architecture shall be established early in the program and involve all dimensions of technical issues as well as customer needs and satisfaction, political pressures and continuity of funding	The systems architecture should be established early and the best judgement of the government and contractor shall be employed on all key issues including use of new or legacy systems	A total systems architecture shall be established early in ordero to provide a sound basis of effectiveness across the broadest spectrum of contractors and operations
C	**System/subsystem design**	System desing shall proceed in a logical and orderly manner through a process of functional decomposition and design traceability that originates with the system functional architecture and results in design specifications for the system	The government customers and contractors shall share the systems design responsbility	The user shall share measures of effectiveness to ensure the proposals selected are those most responsivie to all stakeholders, especially operational organizations
D	**Systems integration and interfaces**	The contractor shall assure the systems integration and interfaces at each level suipports total system functionality across the lifel cycle	The contractor and government shall assure all systems are integrated within themselves as well as interfaced with existing systems	The government shall assure that all operational systems in planning, development or deployed are compatible and mutually supportive in a broad system of systems or family of systems context
E	**Verification/validation**	Every requirement shall have a test and every test shall have a requirement	Government facilities shall be shared to perform V&V and the test criteria shall be shared early	The government shall have the final word on the confidence levels derived from the testing during development, operational test and evaluation and actual deployment and operational use
F	**Deployment and post deployment**	The contractor shall maintain the appropriate engineering and testing capabilities to support gathering, analyzing, and recommending possible changes to the system design or support through reengineering	The government and contractor shall cooperate to conduct an OPEVAL and be open to feeding information back to the program managers to consider design changes or modifications through reengineering	The government shall ensure a proper OPEVAL occurs and that all data gathered from the tests be evalauted for potential recommendations for system modification, redesign, or reengineering. Pre planned improvements are encouraged
G	**Life cycle support**	All design activities shall be viewed from an entire life cycle perspective	A balance of methods, measurements, technologies and processes shall be employed to support the entire life cycle	Funding support across the life cycle shall be maintained and early development programs shall recognize the importance of controlling total ownership cost
H	**Risk assessment and management**	Risks shall be identified, prioritized and mitigated at all levels. Risk is associted with cost, schedule and technical dimensions	The government shall ensure risk management is part of the contractors systems engineering management plan (SEMP) and risks are presented at all program reviews	Risk management at all levels shall be an essential and inherent part of systems engineering, program planning and life cycle activities
I	**System and program management**	Every program shall have a SEMP tailored to that program. The contractor shall also develop a team of capable systems engineers	Systems engineering shall b e recognized and supported throughout progam development and management	The government shall establish security levels for programs to protect crucial technologies and special capabilities

Using the framework enables the researcher to follow a common approach to examine the details of a program. Understanding the successes and failures of a program reveals the benefits and penalties they incurred which can be leveraged to avoid repeating the same mistakes and identify similar opportunities for success. The Secretary of the Air Force directed several initiatives to revitalize the systems engineering community using case studies of programs within the Air Force and NASA. The Air Force Institute of Technology and NASA wrote a series of systems engineering case studies about the A-10 Thunderbolt (Jacques and Strouble 2010), F-111 (Richey 2005), Global Positioning System (O'Brien and Griffin 2007), Hubble Space Telescope (Mattice 2003), International Space Station (Stockman, Boyle, and Bacon 2010), B-2 bomber (Griffin and Kinnu 2007), C-5 Galaxy (Griffin 2004), Theater Battle Management Core System (TBMCS) (Collens and Krause 2005), KC-135 Aircrew Training System (Chislaghi, Dyer and Free 2010), Global Hawk (Kinzig 2010) and the Miniature Seeker Technology Integration (MSTI) (Grenville, Kleiner, and Newcomb 2004). Each case study identified "learning principles" capturing significant aspects across the systems engineering, risk management and program management support activities. Most of the case studies implemented a Friedman and Sage framework to capture the learning principles. Examples of some of the learning principles captured are listed below in Table 9.

NASA acknowledged the value of case studies. The *Challenger* and *Columbia* shuttle accidents, errors with the Hubble telescope, oversight from Congress and the fact two-thirds of their workforce is approaching retirement provides strong motivation to avoid repeating mistakes and capture opportunities for improvement. NASA has over 50 case studies to capture learning principles. NASAs GSFC *Case Study Methodology* (NASA 2011, 3-8) outlines their approach for an effective case study. These steps are:

1. Pick a target, preferably something which will offer insight to others
2. Define the parameters of the case
3. Do the homework and background research
4. Interview the key players to get their story
5. Evaluate the story lines for learning points
6. Draft the case into a narrative

7. Circulate the draft
8. Test the case with a local audience
9. Create a teaching note an epilogue
10. Validate, publish and roll out the case

Table 9. Examples of Case Study Learning Principles

Case Study	Learning Principles (LP)
F-111	Richey (2005, 6) identified the following learning principles: LP1- Requirements definition and management were poorly conceived and difficult to achieve. The attendant specifications made the F-111 system development extremely costly, risky and difficult to manage. LP2- Systems architecture and design trade-offs- System engineering managers were not allowed to make important tradeoffs needed in order to achieve a design balanced for performance, cost and mission effectiveness and the related risk and schedule impacts. LP3- Communications and systems management- Poor communications between Air Force and Navy staffs and over management by the Secretary of Defense and Congress prevented the System Program Office director from applying sound systems engineering principles. LP4- Validation and Verification- Areas of risk and deficiencies were discovered during RDT&E even though there was perceived low risk in the design. LP5- Program Management- Cancellation of the Navy's participation in the F-111 program came after the design was frozen causing enduring impacts on the Air Force F-111 performance and cost.
TBMCS	Collens and Krause (2005, 6) identified the following LP LP 1- The requirements process for producing the first release of TBMCS was broken. The user and acquisition communities never were on the same page. The users did not write a CONOPS or update the original ORD. The acquisition community wrote a technical requirements document for the contractor to develop their system-level specifications. None of these documents were aligned causing further confusion.
B-2	Griffin and Kinnu (2007, 53) identified this LP. LP 4- Subsystem Maturity- Identification that a number of aeronautical systems did not meet the performance baseline configuration forced a reconfiguration of a number of subsystems resulting in a 18 month schedule slip.

The SPAWAR chief engineers office developed a number of SE and SOSE studies including their Information Dominance Enterprise Architecture (IDEA) which seeks to outline the way forward for achieving mission assurance. While these are not case studies these documents reflect the growing role of SOSE in integrating and delivering capabilities to the warfighter. The Navy Capability Evolution Process (NCEP) (SPAWAR 2012) model shown below in Figure 21 is being applied to align the systems being developed and procured to have traceability from the joint level downwards. Thus the mission capabilities are addressed at the appropriate level along with the notional evolution of capabilities moving forward. For example if a joint STK mission capability is needed the high level capabilities are defined in the Joint Capabilities Development System. The capabilities are broken down into SOS or family of system (FOS) portfolios of capabilities such as communications. The SOS or FOS capabilities are broken down further to the platform level. Finally the systems needed onboard the platform are defined at the lowest level.

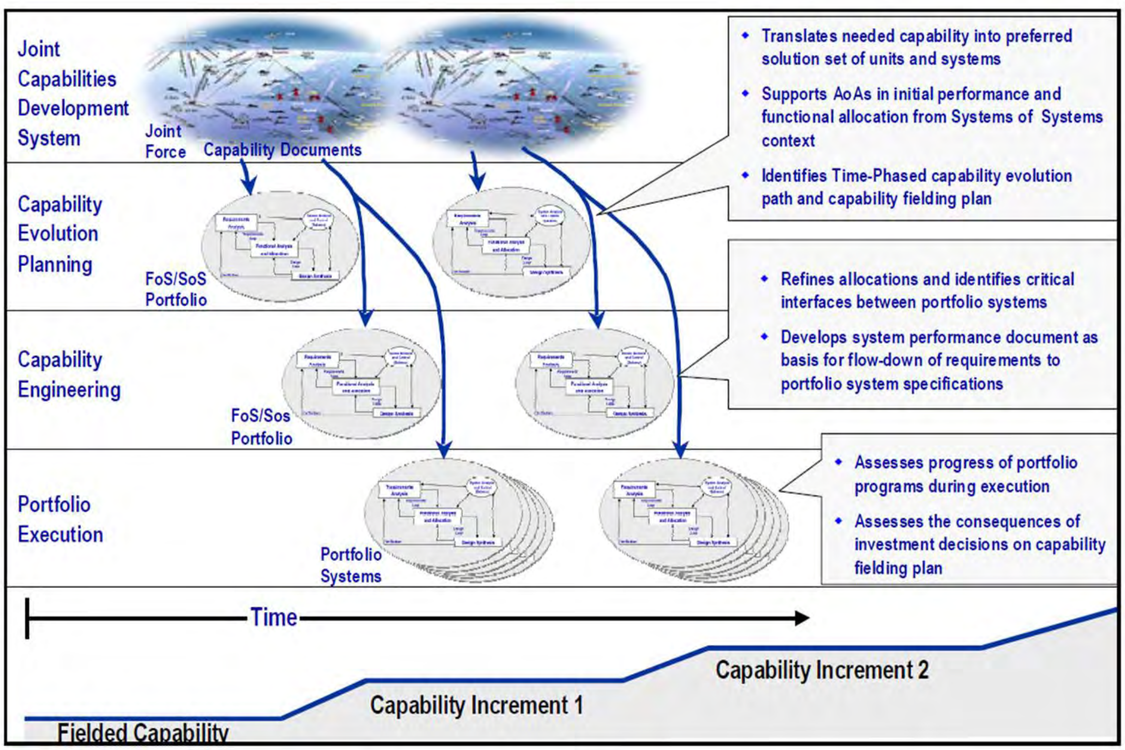

Figure 21. Naval Capability Evolution Process Model (from SPAWAR 2012, 6)

SPAWAR Systems Centers Atlantic and Pacific have various resources they develop and post within their technical libraries available to their workforce. The SPAWAR SOSE and integration “Vee” shown in Figure 22 is one example of the products used to illustrate SOSE processes. The Vee shows the division between the SOSE and the SE activities. Starting from the left the SOS activities follow a similar process as the NCEP model to break the mission SOS into the platform SOS to the constituent systems. The right side is the validation and verification as each system is tested with a platform SOS and ultimately the mission SOS environment. The *Systems Engineering Guide for Systems of Systems* (Director, Systems and Software Engineering 2008) describes seven core elements to be applied to the SOSE process. These are similar to the NCEP model to translate mission SOS capabilities into specific requirements at the SOS and systems levels (SPAWAR 2012). The evolution of SOS is considered since capabilities change over time. Continually assessing the capabilities and evolving the architecture become additional considerations where SOS engineer engages with the SOS and systems teams. By applying the SOSE Vee processes, changes can be managed and fielded with minimal impact to the larger SOS.

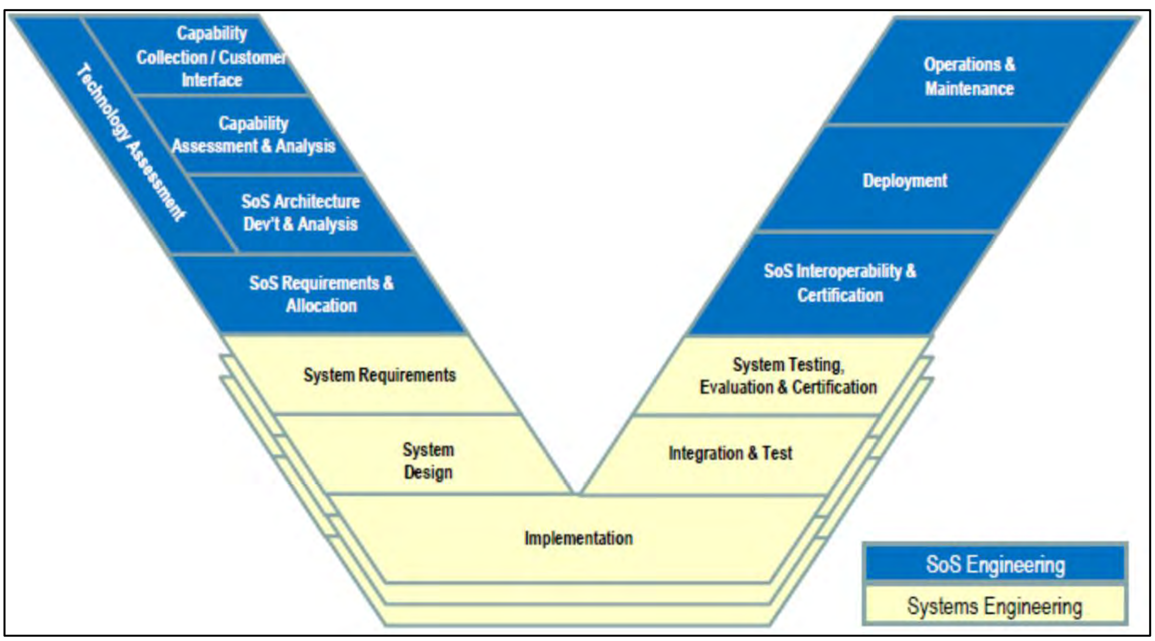

Figure 22. System of Systems Engineering and Integration “Vee” (from Vaneman and Budka 2013)

Submarine communications have evolved from simple single function systems to multi-function integrated systems. The creation of SCSS proved a system of systems approach would work and set the groundwork for establishing CSRR as a formal system of systems program. As a formal program, CSRR has a body of required acquisition, engineering, and logistics documentation which can be used to support creating a case study. This literature review identified a body of information available concerning the purpose of a case study and the benefits. Additionally there is a significant amount of information available about systems and systems engineering. There is also substantial evidence DOD has been moving toward system of systems and system of systems engineering as disparate capabilities are increasingly integrated. Despite this move, most of the literature regarding system of systems engineering, integration and policy has been relatively recent.

III. METHODOLOGY

The methodology used for this research looked at a logical manner of providing the necessary background and context in order to understand the reasons for some of the activities which occurred and the overall impact, either positive or negative. The research questions were bounded by the purpose to aid in providing background and context. The purpose of this case study was used as a basis for the research questions and they are listed below.

1. The history of submarine communications leading up to the creation of the CSRR program.
2. The organizational structure of the CSRR program.
3. The relationship with other programs of record and stakeholders.
4. System of systems architecture management.
5. The advantages and disadvantages of the CSRR SOS approach within the various disciplines (e.g., modernization, integrated logistics support (ILS), training, sustainment, and information assurance (IA)).
6. Process improvement initiatives and their impact in regard to cost, schedule and performance.
7. CSRR's ability to meet future mission requirements while supporting current missions

The wide scope for this case study is necessary given the history of submarine communications leading up to CSRR and amount of activity that has occurred. Maintaining focus on the purpose ensures we are addressing the correct topics while the scope ensures the questions are reasonably bounded so they could be answered in a reasonable manner. The scope was applied in the methodology and is listed below.

1. The development of submarine communications from its initial beginnings up through the deployment of CSRR increment one version three.
2. The organizational structure of the CSRR program to include the design and development group, production and installation group, ILS and training groups, IA groups, and sustainment group.
3. The version development process, its strengths and weaknesses.
4. SOS architecture management with other programs of record and portfolio capability management, the relationships with the other programs of record and the warfighter.

5. The advantages and disadvantages of the CSRR system of systems approach regarding ILS, training, production, installation (synchronization of installations into block upgrades), IA and sustainment.
6. Assessment of requirements in a changing environment with regard to the Undersea Connectivity Roadmap, Design for undersea warfare, PEO C4I Master Plan, and the way ahead for considering disruptive technologies.
7. An evaluation of the process improvement initiatives and their influence and impact in regard to cost, schedule and performance.
8. The future of CSRR in today's environment and tomorrow up through 2030.

The methodology for this case study consisted of the following activities.

1. Investigation into other case studies to determine if other researchers had performed similar work and confirm if a case study would be an appropriate approach. Review of other case studies did indicate similar work had been done and several case studies addressed SOS issues.
2. Investigation into Navy and specifically PEO C4I archives to determine if any case studies had been written. No case studies could be located in the SPAWAR and PEO archives or technical libraries.
3. Review of the DOD acquisition and program documentation regarding SOS, defense acquisition requirements, systems and system of systems principles and how to measure the characteristics of a SOS. A large amount of information is available for acquisition, systems engineering and systems engineering principles both locally and online. Most of the system of systems literature has been developed in the last 14 years.
4. Perform an in depth analysis of the CSRR program documentation. This includes the formal program documentation and minutes from the various integrated product teams (IPT) supporting the program. The documentation provided insight to the history, requirements and policies for managing the CSRR program.
5. Conduct selected interviews with subject matter experts (SME) with regard to developing and managing a SOS program and the individual systems supporting the SOS. Interviews were conducted with key members of the engineering and production teams.
6. Synthesize the information to capture lessons learned (or learning principles), develop conclusions and make recommendations for further consideration. A derivative of the Friedman-Sage framework will be used since contractor involvement is limited.

Initial research began identifying background information concerning case studies related to systems engineering and system of systems engineering to determine if a case study approach would be appropriate. Eleven case studies were identified and read. These case studies are listed in Table 10.

These case studies were reviewed in order to understand the reasons they were performed, how they were accomplished and what significant lessons were identified. Research of these case studies looked for common themes. Several case studies acknowledged they were part of a SOS (GPS, TBMCS). The learning principles were compared against the lessons learned from the CSRR program.

Most of the case studies used the Friedman and Sage framework to capture learning principles. Several of these case studies included their learning principals as part of the whole document and the remainder provided in a separate executive summary. Examples of learning principles identified were compared against the CSRR program lessons learned to determine if commonalities existed.

Table 10. Case Studies Used in This Research

Case Study	**Sponsor**
KC-135 Flight Simulator	Air Force Center for Systems Engineering
Global Positioning System	
International Space Station	
F-111 Aardvark	
C-5A Galaxy	
Hubble Space Telescope	
A-10 Thunderbolt II	
Theater Battle Management Core System	
Global Hawk	
Miniature Seeker Technology Integration	Virginia Polytechnic Institute and State University
V-22	U.S Army Command and General Staff College

Online research of the PEO and SPAWAR process activity libraries, Naval Systems Engineering Resource Center and Systems Engineering Environment, located applicable SE and SOSE policy documents. However, no case studies were located in the repositories. While case studies are available through other online means there is no central, easily accessible source for SPAWAR and PEO C4I engineering and program personnel.

Several SMEs were interviewed to capture their insights regarding the design, production, and sustainment of CSRR as a SOS. NUWC and SSC LANT maintain the core teams of SMEs responsible for the design, development, testing, production and sustainment. The sample size of this research was limited to the people involved with the CSRR program for the last ten years. The CSRR chief engineer, technical project manager, design agent and production agent were interviewed to capture their responsibilities and insight to design and manage CSRR as a SOS. These interviews took place via email and telephone. The interviews were limited to the background of submarine communications immediately preceding CSRR and development from V0 through V3.

CSRR is a recognized acquisition program and maintains the required acquisition, technical, and logistics documentation. The CSRR documents listed in Tables 11 through 13 were reviewed to ascertain what information could be used to support a case study.

Table 11. CSRR Acquisition Documents Reviewed

Document	Purpose of Document
Acquisition/Programmatic	
Mission needs statement for the Integrated Maritime Communications System (CNO N81 1995)	Original statement of requirement to fill a capability gap. This would be the Initial Capabilities Document under the JCIDS process.
Common Submarine Radio Room Capabilities Production Document (PMW770 2006)	Defines the production elements applicable to CSRR increment one
Submarine Exterior Communications System Capstone Requirements Document (CNO N8 1998; CNO N8 2003)	Similar to a Capability Description Document (CDD) it defines the key performance parameters and key systems attributes
Submarine Communications Master Plan (CNO N87 1995; CNO N61 and N87 1998)	Part of the submarine force strategic plan consolidating current and future communications requirements in support of the budget planning process
CSRR Acquisition Strategy/Acquisition Plan (PMW770 2008)	Outlines the business and technical acquisition management approach in order to achieve the program objectives within the allotted resources
Concept of operations for CSRR Inc1 V2 and Inc 1 V3 (PMW770 2011b)	Defines the overall intent of a particular mission or strategy. The CONOPS provides a high level view of how a system will be employed
Design for Undersea Warfare (Richardson, Caldwell and Breckenridge 2011)	Commander Submarine Force guidance for executing their "lines of effort" for maintaining readiness for operations, maximizing effectiveness during deployments and develop future capabilities
PEO C4I Strategic Plan 2013-2018 (Burroughs 2012)	PEO guidance for delivering capability and reducing variance
Undersea Connectivity Roadmap (Hendricks and Duffy 2012)	Undersea enterprise vision of future capabilities for communications and undersea connectivity
DOD Inspector General (IG) report on CSRR (2005)	IG investigation into the performance of the CSRR program

Table 12. CSRR Engineering Documentation Reviewed

Technical	
System Engineering Plan (PMW770 2007)	Defines the programs strategy for managing all of the technical activities related to systems engineering
Test and Evaluation Master Plan (PMW770 2012a)	Defines the overall test strategy and resources needed to accomplish all required developmental and operational testing
System Subsystem Design Description for CSRR Inc1 V3 SSBN (NUWC 2008), VA (NUWC 2012) and LA (NUWC 2011)	Provides program background and describes the physical and functional designs of the capabilities within each version.
Systems Design Verification Test Plan for CSRR Inc1 V3 LA (NUWC 2011), VA (NUWC 2012b), SSGN (PMW770 2013a), and SSBN (PMW770 2013b)	Defines the testing parameters to verify CSRR can meet all performance requirements outlined in the CPD. Supports the TEMP as part of the overall testing strategy
CSRR System Requirements, Design, Integration and Testing Process (Ross 2013)	An internal document developed to aid new team members in familiarizing themselves with the CSRR program
CSRR Circuit Matrix (PMW770 2014)	A formal agreement between PMW770 and the submarine force which details which circuits will be supported by a particular CSRR version and platform class

Table 13. Logistics and Training Documentation Reviewed

Logistics	
Integrated Logistics Support Plan (PMW770 2008b)	Supports the CSRR acquisition strategy and defines the sustainment strategy for the overall program
CSRR Navy Training Systems Plan (CNO N2N6 2012)	Service specific training systems plan which serves as the agreement between the program stakeholders
CSRR Reliability, Maintainability, and Availability (RMA) reports	Periodic reports from the Navy's independent assessor for RMA data collected from maintenance, material and management (3M) system

In 2008 the Deputy Secretary of Defense issued a policy directing all DOD activities to begin using Lean Six Sigma (LSS). The CSRR program performed a number of improvement activities in order to improve meeting cost, schedule and performance. These improvement activities were reviewed as well to determine what issues occurred, their root cause and their solutions. Table 14 is a summary of the continuous improvement events using LSS.

In order to gain a better understanding of the SE and SOSE processes used by other DOD and government organizations an investigation into the differences and benefits between systems engineering and systems of systems engineering was accomplished. These references were located on the INCOSE website, Defense Acquisition Portal Acquisition Community Connection, Dudley Knox library, and other recognized sources such as MITRE and Massachusetts Institute of Technology (MIT). Table 15 is a summary of the types of documentation examined.

Table 14. Continuous Process Improvement Activity Documentation Reviewed

Process Improvement Events	
CSRR version value stream analysis (VSA)	Lean event to evaluate how to shorten the CSRR development cycle following the deployment of CSRR V0
RFDACS reliability assessment	Lean six sigma (LSS) event to analyze system failures, identify the root cause and develop improvements for increasing system A_o
CSRR testing streamlining rapid improvement event	LSS event to identify non-value added activities in the test and certification process and identify areas where testing can be leveraged
CSRR modernization other productivity improvement event	LSS event to capture the benefits of performing consolidated installations during available modernization periods
CSRR integration streamlining rapid improvement event	LSS event to revisit the original CSRR VSA and attempt to address configuration variance issues identified during the employment of CSRR V3

Table 15. Other Applicable Engineering Documents Reviewed

Other engineering documents
INCOSE Systems Engineering Book of Knowledge (Adcock 2014)
OSD Systems Engineering Guide for System of Systems (Director, Systems and Software Engineering 2008)
DSMC Systems Engineering Fundamentals Guide (DSMC 2001)
NASA Systems Engineering Guide (NASA 2007)
MITRE System Engineering Guide (MITRE 2014)
DOD Systems Engineering annual reports released by the GAO
SOS modeling and acquisition

The methodology outlined the plan of action to identify and accumulate information to complete the case study. Once all of the information was identified and collected, the initial analysis developed the framework for the case study. Research using the information from the systems engineering classes provided a starting point for developing the research questions and a plan to answer them. Further investigation of the local and online resources including SPAWAR, PEO C4I, PMW770, Dudley Knox library and the Defense Technical Information Center portal located CSRR program documentation and related SE and SOS information. The information was collected and analyzed to answer several of the questions presented in this thesis about defining CSRR as a system of systems. The results in turn derived further answers to the remaining questions for effectively developing and managing comparable system of systems. Lessons learned or learning principles were validated and any new ones were identified.

IV. APPLICATION OF METHODOLOGY

The methodology outlined in the previous chapter will answer the research questions. The results were used to identify learning principles applicable to CSRR as a system of systems. These learning principles were also assessed to determine if they could be extended to other programs or system of systems. A number of these can serve as an opportunity to avoid mistakes and identify prospects that would otherwise be missed. Each of the research questions will be answered in more detail.

A. EVALUATION OF THE CASE STUDIES

The first step to developing this case study began by reading other case studies to determine what they are and decide if using a case study approach would be appropriate. Friedman and Sage (2003, 84–86) stated case studies serve a valuable purpose by exposing a student to real world examples of systems engineering. Their stated position is a case study is an "empirical inquiry that investigates contemporary phenomenon within a real-life context, especially when boundaries between the phenomenon and context are not clear and multiple sources of evidence is used" (Friedman and Sage 2003, 85).

There are several benefits of performing a case study (Friedman and Sage 2003, 85). Understanding the how and why, revealing the detailed information surrounding an event, and allows exploration of a topic when a strong theory may not be available. The sources of evidence available to conduct research include looking at documentation, records, interviews and observations. Using more than one approach can add detail and context. One of several approaches such as pattern matching, explanation building, logic models, and time series or cross case analysis can be used to analyze the collected information.

An initial search was performed to determine how much information about case studies existed. Using Google, a search for "case studies" returned over 25 million possible results. Extending this further to include the term "system of systems" narrowed the results to over 350,000. The search for identified case studies written by the Air Force and NASA concerning the Hubble space telescope, F-111, Global Hawk, TBMCS, MTSI

and others. A search of the Dudley Knox Library identified over 9,000 possible results. For the term "navy system engineering case studies" identified 96 possible candidates. Performing a more detailed search for a "navy engineering system of systems case studies" identified only five hits, none of which pertained to the search. Searches of the Defense Acquisition University portal identified a number of case studies including the ones used in this study.

The SPAWAR chief engineers web portal maintains the process activity library as a repository and workspace for SE and SOSE documentation related to the information dominance enterprise architecture (IDEA) (SPAWAR 2014a). The IDEA is attempting to define the way forward for developing and delivering future C4I strategic level objectives in support of information dominance capability to the warfighter. Figure 23 shows how the IDEA disassembles the enterprise SOS architecture into more discrete requirements and systems. Using a process similar to the NCEP and the Vee the objective requirements are decomposed to the mission and service requirements. These requirements are then assigned to the specific programs to develop and acquire the applicable systems.

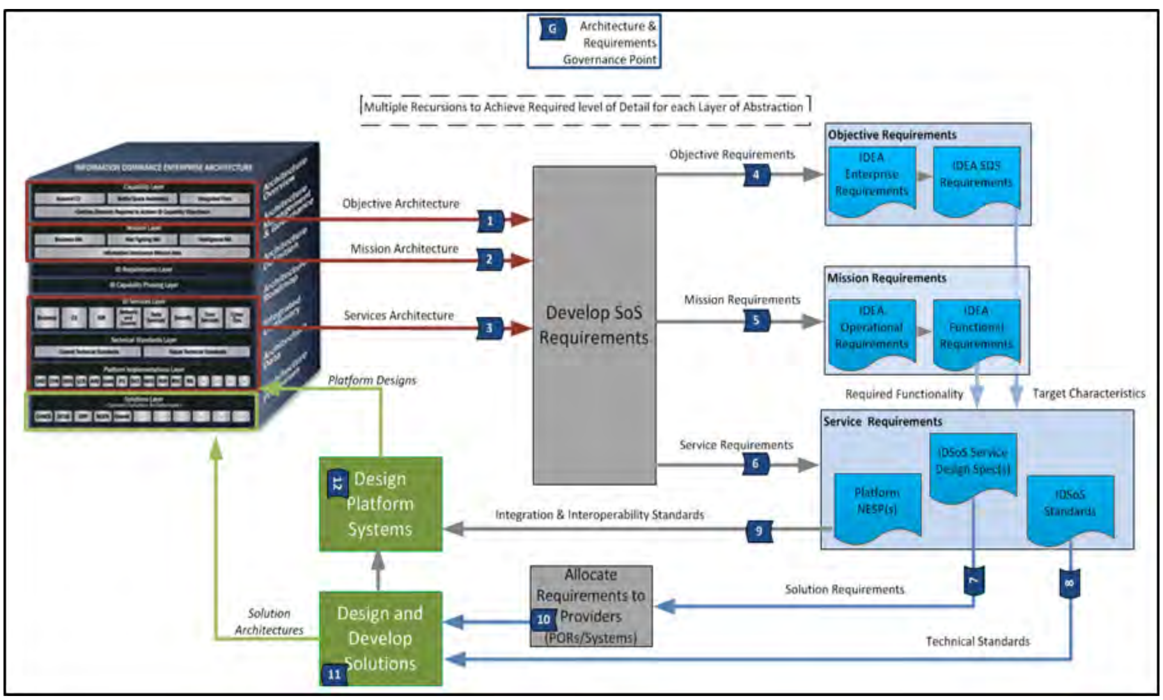

Figure 23. SPAWAR Information Dominance Enterprise Architecture Requirements Tree (from SPAWAR 2014b)

Additional searches of the PEO C4I and SPAWAR technical repositories revealed no SPAWAR systems case studies were available. SSC PAC maintains a technical library to support their science and engineering activities, but no case studies were available for systems under their purview. SSC LANT maintains a limited technical library primarily devoted to holding various drawings. The CSRR design agent was also asked if NUWC Newport maintains a technical library. Their technical library mainly handles drawings and technical publications requested by the staff (Steve Devin 2014, email questionnaire). The availability of any related engineering case studies could not be confirmed.

The case studies confirmed the approach would be appropriate for the goals of this study. Ten case studies used a Friedman and Sage framework or a slight derivative while the MSTI and V-22 created a different approach to lessons learned. Several of the case study learning principles were provided in an executive summary and were not available. For these case studies, such as the KC-135, significant items were identified and presented as learning principles. In all cases there were other topics which represented possible learning principles as well. For this study the evaluation was limited to the ones presented in the executive summary or extracted if a summary was not available. An initial evaluation identified the framework domains addressed from each case study as seen in Table 16.

Table 16. Summary of Domain Areas Impacted by Each Case Study

	Programs										
Framework Domain Areas	**A-10**	**TBMCS**	**B-2**	**C-5A**	**Hubble**	**ISS**	**GPS**	**F-111**	**GH**	**MTSI**	**KC-135**
A. Requirements Definition and Management	X	X	X	XX	X	X		X	XX		X
B. Systems Architecting and Conceptual Design	XX	X	X		XX	X	X	X		X	X
C. Detailed System and Subsystem Design and Implementation	X	X	X		X	X	XX		X	X	X
D. Systems and Interface Integration	X	X			X	X	XX	X	X		
E. Validation and Verification		X				X			X		
F. System Deployment and Post Deployment	X										
G. Life Cycle Support	X				X						X
H. Risk Management	X		X	X			X	X	X		X
I. System and Program Management			X	XX	X	XXX	XX	XX	X	XXX	X

All of the case studies used the Friedman and Sage framework except for the MSTI and the V-22. The MSTI lessons were applied to the Friedman and Sage domains based on this researcher's assessment. The V-22 case study was not written to assess the application of systems engineering principles so it was removed from further consideration. The eleven case studies were then assessed to determine if there were correlations between the earlier case studies and CSRR. Each case study identified areas which were related to similar issues with CSRR. For example the TBMCS team had not engaged with the user community to develop a CONOPS, the systems architecture did not have adequate detail and interface management was poor or nonexistent. Another example using the B-2 identified a failure to recognize a maturity issue needed attention, which resulted in a five month delay and missing the Critical Design Review (CDR) milestone (Griffin and Kinnu 2007, 53). The F-111 described the problems faced by the engineering team when a major stakeholder chose to pull out of the effort which had lasting and substantial impacts on the program (Richey 2005, 30–31).

Similar challenges exist for CSRR in that individual systems may not have a CONOPS, or if they do, it is not uncommon for them to conflict with another. This might appear to be in conflict with the JCIDS but a large number of programs had been developed prior to JCIDS being fully implemented. If the program was post milestone they were grandfathered and the existing documentation was accepted to support that particular milestone decision. Oversight of ACAT I programs, minimal oversight of other ACAT programs beyond budgetary cycle requirements and infrequent reviews of systems once in sustainment deter assessing if a system is aligned to a mission SOS.

Systems architecture is defined for the individual system but illustrates itself as operating as a piece in the global architecture and not necessarily in the intermediate architecture which would include CSRR or SWFTS. Interfaces are usually defined at the system level but routinely do not interoperate with other systems, forcing some type of middleware solution. Several authors acknowledged they were working within a SOS architecture while conducting their case study on the area of interest. The specific learning principles or lessons learned from these case studies are listed below in Table 17.

Table 17. Learning Principles by Case Study and the Associated Domains Affected

System Case Study	Associated Friedman and Sage Domains
A-10 Thunderbolt II Warthog (Jacques 2010)	
LP-1 The system concept and preliminary design must follow, not precede, the mission analysis.	A. Requirements Definition and Management B. Systems Architecture and Conceptual Design C. System and Subsystem detailed design and implementation
LP-2: Prototyping can be used to help manage technical and cost risk at the system, subsystem, and component level.	H. Risk Assessment and Management
LP-3: Clear lines of responsibility must be established to ensure successful integration, especially when multiple programs are involved.	D. Systems Integration and Interface
LP-4: The government must ensure the contractor is able to "Walk the Talk" when it comes to production.	G. Life Cycle Support H. Risk Assessment and Management
LP-5: Successful design, development and production is not enough to sustain a system throughout its life cycle.	F. Deployment and Post Deployment
LP-6: If the politics do not fly, the system never will.	B. Systems Architecture and Conceptual Design
Theater Battle Management Control System (Collens and Krause 2005)	
LP-1: The government did not produce a Concept of Operations, key operational performance parameters, or a system specification for the contractor. The requirements baseline was volatile up to system acceptance, which took place after operational test and evaluation.	A. Requirements Definition and Management.
LP-2: The system architecture was defined at too high a level, which had a tremendous impact on system design and development.	B. System Architecture.
LP-3: The system and subsystem design was severely hampered by the complexity of legacy applications, misunderstanding of the maturity and complexity of commercial and third party software products, and a lack of understanding of how the system would be employed by the user.	C. System/Subsystem Design
LP-4: Systems and interface integration was highly complex. The external system interfaces were not managed and were often impossible to test at the	D. Systems Interface and Integration

System Case Study	Associated Friedman and Sage Domains
contractor's facility.	
LP-5: The lack of a firm requirements baseline made validation and verification very difficult. Not being able to replicate the operational environment prior to acceptance test created severe problems.	E. Validation and Verification
B-2 Spirit Bomber (Griffin and Kinnu 2007)	
LP-1: Integration of the Requirements and Design Processes. A key aspect of the implementation of the systems engineering process was the integration of the SPO requirement's team with the contractors' work breakdown structure task teams into a cohesive program effort.	A. Requirements Definition and Management.
LP-2: Work breakdown structure task teams and functional hierarchy. A well-defined contract work breakdown structure stipulated the entire program content and tasking.	I. System and Program Management
LP-3: Air vehicle reconfiguration. When the identification of a major aeronautical control inadequacy was discovered just four months prior to formal configuration freeze, an immediate refocus of the task teams was required.	B. Systems Architecting and Conceptual Design
LP-4: Subsystem maturity. The effect of the reconfiguration on the maturity of all the air vehicle subsystems (flight control, environmental control, electrical, landing gear, etc.) was far greater than projected.	C. System and Subsystem detailed design and implementation
LP-5: Risk planning and management. The program was structured so that risks affecting the viability of the weapons system concept were identified at contract award and were structured as part of the program and work breakdown structure work plans.	H. Risk Assessment and Management
C-5A Galaxy (Griffin 2004)	
LP-1: The process for developing and documenting the system performance requirements involved the user, planners, developers, and technologists from both the government and industry in a coordinated set of trade studies. It resulted in a well-balanced, well-understood set of requirements that fundamentally remained unchanged throughout the program.	A. Requirements definition and management
LP-2: The total package procurement concept (TPPC) employed by the government required a fixed-price, incentive fee contract for the design, development, and production	H. Risk Assessment and Management I. System and Program Management

System Case Study	Associated Friedman and Sage Domains
LP-3: A weight empty guarantee was included in the specification as a performance requirement and in the contract as a cost penalty for overweight conditions of delivered aircraft. The weight empty guarantee dominated the traditional aircraft performance requirements (range, payload, etc.), increased costs, and resulted in a major shortfall in the wing and pylon fatigue life. The stipulation of a weight empty guarantee as a performance requirement had far-reaching and significantly deleterious unintended consequences.	A. Requirements Definition and Management
LP-4: The system program office employed independent review teams to assemble national experts to examine the program and provide recommendations to the government. These problem-solving teams were convened to garner the best advice in particular technical areas: structure design and technology, and designs to achieve useful service life.	I. System and Program Management
Hubble Space Telescope (Mattice 2003)	
LP-1: Early and full participation by the customer/ user throughout the program is essential to success.	A. Requirements definition and management
LP-2: The use of pre-program trade studies to broadly explore technical concepts and alternatives is essential and provides for a healthy variety of inputs from a variety of contractors and government.	B. Systems Architecting and Conceptual Design
LP-3: A high degree of systems integration to assemble, test, deploy, and operate the system is essential to success and must be identified as a fundamental program resource need as part of the program baseline.	C. System and Subsystem detailed design and implementation D. Systems Interface and Integration
LP-4: Life cycle support planning and execution must be integral from day one, including concept and design phases. The results will speak for themselves.	B. Systems Architecting and Conceptual Design G. Life Cycle Support
LP-5: For complex programs, the number of players (government and contractor) demands that the program be structured to cope with high risk factors in many management and technical areas simultaneously.	I. System and Program Management
International Space Station (Stockman, Boyle and Bacon 2010)	
LP-1: Systems engineering involves communications, critical to international partnerships, so before worrying about technical interfaces, make sure the	I. System and Program Management

System Case Study	Associated Friedman and Sage Domains
integrated product teams and communication bandwidth between partners are optimal.	
LP-2: Maintaining a high level of competent and experienced personnel over a two decade long program requires strategic level planning and execution of workforce planning.	I. System and Program Management
LP-3: Do not be so ready to chase revolutionary designs over evolutionary designs. A key lesson from Russian experience (such as the Soyuz) is that it is often less risky to stay with a known design and provide minor improvements.	B. System Architecture and Conceptual Design
LP-4: Multi-element integrated testing with actual hardware, high fidelity simulators and connectors is critical and must be in the program from day one	E. Validation and Verification
LP-5: In an ISS like project where so many different countries and companies contribute hardware and software, the interfaces must be extremely simple.	C. System and Subsystem detailed design and implementation D. Systems Interface and Integration
LP-6: Do not be too quick to allow partners (or NASA) to start building modules or expensive experiments too far in advance of locking in schedule and program baseline	A. Requirements Definition and Management I. System and Program Management
Global Positioning System (Griffin and O'Brien 2007)	
LP-1: Programs must strive to staff key positions with domain experts.	I. System and Program Management
LP-2: The systems integrator must rigorously maintain program baselines.	C. System and Subsystem detailed design and implementation D. Systems Interface and Integration
LP-3: Achieving consistent and continuous high-level support and advocacy helps funding stability, which impacts systems engineering stability.	I. System and Program Management
LP-4: Disciplined and appropriate risk management must be applied throughout the life cycle.	H. Risk Assessment/Management
LP-5: The GPS case study highlights the need for systems thinking throughout.	B. System Architecture and Conceptual Design C. System and Subsystem detailed design and implementation D. Systems Interface and Integration

System Case Study	Associated Friedman and Sage Domains
F-111 (Richey 2005)	
LP-1: Ill conceived, difficult to achieve requirements and attendant specifications made the system development extremely costly, risky and difficult to manage. The state of technical maturity was not well understood by either contractor or government in the case of inlet-engine compatibility (dynamic distortion) and structural fracture mechanics of brittle materials.	A. Requirements Definition and Management
LP-2: Systems engineering managers were not allowed to make important tradeoffs that needed to be made in order to achieve an effective design that was balanced for performance, cost and mission effectiveness and the attendance risk and schedule impacts. The government provided the systems architecture specifications and the contractor responded, although there were concerns expressed by Navy and Air Force analysts that the disparate range of system architecture requirements could be met while maintaining the required level of commonality.	B. System Architecture and Conceptual Design D. Systems Interface and Integration
LP-3: The program suffered from poor communications between Air Force and Navy technical staffs and from over management by the Secretary of Defense and The Director, Defense Research and Engineering and received intense congressional scrutiny, restricting the program office from applying sound systems engineering principles.	I. System and Program Management
LP-4: The F-111 had areas of risk or deficiency that came to light during research, design, testing and evaluation even though there was a low perceived risk in the design. The development program introduced concurrency between design validation and verification and production to accelerate the program schedule.	H. Risk Assessment/Management
LP-5: Cancellation of the Navy version after the joint design was frozen and production of the Air Force version was in progress had a lasting impact on the F-111 performance and cost.	I. System and Program Management
Global Hawk (Kinzig 2010)	
LP-1: The Joint Program Office was a very small, austere organization, purposely sized that way to ensure minimal oversight by the Government and	I. System and Program Management

System Case Study	Associated Friedman and Sage Domains
provide a significant degree of autonomy to the contractors.	
LP-2: The program developed a set of desired performance characteristics that were defined in terms of a range of values considered acceptable. The parameters were labeled as goals, either as Primary Objective, Objective, or Desired. This approach gave the contractor the latitude and responsibility to define the balance among the desired performance parameters, so the user would receive the "biggest bang for the buck." This freed the Joint Program Office from closely tracking the contractor's progress in meeting a large number of individual performance specifications. The Joint Program Office even tried hard to avoid giving the impression that they valued one specific performance goal over another.	A. Requirements Definition and Management
LP-3: The risks and problems associated with integrating COTS into a complex system were underestimated.	H. Risk Assessment/ Management
LP-4: The pace of the flight test program was too fast given its cumbersome mission planning process and limited resources. Test personnel were clearly overburdened, which appears to have been a contributing factor in the air vehicle 3 taxi mishap.	E. Validation and Verification
LP-5: With the major reduction in the use of specifications and standards, there was no comprehensive set of requirements to judge that an aircraft was safe to fly. This void in the acquisition process led to the formulation and release of Air Force Policy Directive 62-6.	A. Requirements Definition and Management C. System and Subsystem detailed design and implementation D. Systems Interface and Integration
Miniature Seeker Technology Integration (Grenville, Kleiner and Newcomb 2004)	
LP-1: "Build Porsches, not Formula 1's. Use design margins to reduce the level of optimizing at the sub-system level and take advantage of existing hardware architectures.	B. System Architecture and Conceptual Design C. System and Subsystem detailed design and implementation
LP-2: Use daily meetings and an electronic problem failure report approach to enable peer reviews. Embedding quality assurance with the team allowed problem discovery earlier and resolution earlier in the process.	I. System and Program Management
LP-3: Team took ownership of the project. Each	I. System and Program

System Case Study	Associated Friedman and Sage Domains
responsible engineering authority looked forward to the project horizon. Team members had more responsibility.	Management
LP-5: Keep the team focused to accomplish their objectives.	I. System and Program Management
KC-135 Flight Training System (Chislaghi, Dyer and Free 2010)	
Designing the platform to be compatible with a motion system paid dividends later in the system's lifecycle by providing a growth path which facilitated the implementation of future upgrades. (8)	B. Systems Architecting and Conceptual Design C. System and Subsystem detailed design and implementation
The philosophy employed by the KC-135 aircrew training system senior engineering and management leadership emphasizes the importance of open communication lines between the various stakeholders. (14)	I. System and Program Management
Air Mobility Command has emphasized two key program goals that formed the foundation of the KC-135 aircrew training system upgrade strategy. The first addressed the need for concurrency, which is to ensure the operational flight trainer is upgraded and ready for training prior to the aircraft with its modifications being fielded. The second addressed the goal to upgrade operational flight simulator training effectiveness. The first goal emerged as a result of early successes in the execution of the simulator's upgrade strategy concurrent with a major aircraft upgrade and modification program. (18)	G. Life Cycle Support
There was no formal systems engineering process followed for requirements allocation. (36)	A. Requirements Definition and Management
Added emphasis had to be placed on managing risk mitigation in order to ensure the right people were assigned to work the problem, mitigation plans were realistic and implementable, and that the required work was on track to being completed on schedule. (20)	H. Risk Assessment/Management

B. COMMON SUBMARINE RADIO ROOM SYSTEM OF SYSTEMS DEVELOPMENT AND INTEGRATION APPROACH

As a system of systems, CSRR followed an established and fairly disciplined approach to developing each version. The paradigm shift from simply building a

collection of boxes to actively working with various programs which were in different stages of maturity created many challenges and opportunities. Throughout the entire process from design and development to sustainment these challenges and opportunities influence the CSRR program ability to deliver and support a complex SOS to support the submarine communications requirements.

1. Design and Development

The initial version of CSRR was based on a contractor-furnished design for the VA class. Following a failure by the subcontractor to deliver a system to the shipbuilder PEO SUB performed an analysis of alternatives (AOA). The AOA recommended several options (PMW770 2008, 11).

1. Sole source contract to Electric Boat and Lockheed Martin-Maritime Systems and Sensors
2. A full and open competition and a government-industry team development and production effort
3. Government industry team

Option three was chosen to support the CSRR work for the SSGN. Work from the SSGN development was carried forward and leveraged to support OPNAV's direction to design a CSRR variant for the SSBN. The main requirement of CSRR is to integrate other PORs. Several PORs, such as ADNS, were not ready in time to support the delivery in support of the development efforts so PMW770 developed suitable replacement solutions to support program delivery. This solution enabled CSRR to effectively work as a directed SOS up through CSRR V2. From an SOS perspective CSRR could have been defined as a directed SOS. A benefit of being a directed SOS is CSRR had a large degree of control over design, configuration management and sustainment. The disadvantage is a solution which increased overall total ownership costs (TOC) to the CSRR program.

The original approach for developing each version of CSRR was related to a specific submarine class. The SSGN V0 leveraged the VA V0 design. The SSBN and SW used the SSGN V0 design as a basis for their development. Each of these designs were built and completed a full system design verification test (SDVT) and systems acceptance test (SAT) prior to their introduction to the fleet. SSBN V1 began the next cycle with

SSGN and SW V2 closely following behind. In each case a full design was again built and fully tested to validate the design and verify functionality. For these versions it was not difficult to maintain a single design since only four SSGNs, three SW and 14 SSBNs were operational. The changes to the VA design were incorporated with the shipbuilder to deliver a minimal capability and upgrades occurred as each platform entered a post shakedown availability (PSA). Following PSA responsibility of the VA CSRR shifted to PMW770.

The development of V2 for SSGN and SW attempted to leverage available PORs, but one of the initial problems noted is their equipment had not completed their own testing, was planned to occur concurrently, or it was accomplished without consulting with the CSRR team to assure their approach would work. The maturity of two systems fell behind despite assurances from the POR they would be ready. The first was discovered at the SSGN CDR which forced a significant design change to remove all interface cabling when it failed to deliver a system. Another issue with this program resulted from the CSRR team reconfiguring the system in order to physically fit the components in the design. The program had completed their design environmental testing without engaging the CSRR team to assess its ability to fit in the design. This resulted in invalidating the environmental testing when the components were relocated to fit in the radio room. The other occurred when the POR reported their software would be delayed one year. This was identified just prior the beginning of the installation. The CSRR program had agreed to procure the hardware but the lack of software forced development of a temporary solution.

A similar issue occurred with the SSBN V1 when modifications to an antenna system did not complete all of their design work in time to support the scheduled modernization period. While the CSRR and antenna modernization were related but separate efforts it still represented a lack of synchronization of activities. Several agreements were established with ADNS and other programs to arrange a shift of sustainment responsibilities and to agree upon the delivery of POR systems in the future.

At this time, the LA class, originally deferred from FY10 to FY15, were accelerated to reach a planned IOC in FY12. Since the LA class constituted the majority

of the submarines in the force and was already facing obsolescence issues, it was selected to be the first V3 platform. In 2009, the CSRR V3 preliminary design review (PDR) initiated a transition from an informal directed SOS to a recognized acknowledged SOS utilizing other POR systems to deliver capability. A benefit of this approach more closely aligned CSRR development with the direction of the program acquisition plan (AP) to fully leverage other POR systems. One advantage of this shift in approach is the reduction of TOC for the CSRR program. Reduction of overall SOS TOC is questionable since these costs were spread across a number of programs. Another advantage is the CSRR team no longer had to identify and procure these components. The disadvantage is the number of configuration management and logistics challenges increased with each new POR as they introduced changes in their systems. These changes had to be assessed for their impact to the overall SOS design. Using the other PORs in many cases identified their designs had to be modified in order to be accommodated physically and functionally. Changes to the system designs had to be negotiated with the POR which in turn impacted cost and schedule (Steve Devin 2014, email questionnaire). In one case SDVT had to be halted to identify the source of heating issues in the inboard racks. The issue was resolved through reversing component fans, fixing cooling shorts and redirecting more cooling to the radio room. The outcome of this approach identified the need to engage with the PORs earlier to ensure any submarine unique requirements were included in their documentation.

Another issue was identified just prior to beginning the first installation impacted the certification of the messaging system. The change in its certification forced a change how information could be routed. A solution was identified but was not installed on the first platform. The increased density of cables and network components in the radio room created cable management issues which increased the difficulty of racking out equipment. This was first noted by the production team as they assembled the production kits in their facility for pre-installation testing and checkout (PITCO). The issues were confirmed on the first several platforms which in turn forced a redesign effort to strengthen cable retractors and reroute cabling. The number of issues found confirmed more maturation of POR components was needed prior to beginning integration into the CSRR architecture.

Additionally closer coordination between the design and production team needs to occur in order to identify issues impacting production, installation and maintainability.

Effectively managing an SOS program such as CSRR requires creating and maintaining effective teams. The NUWC design team, shown in Figure 24, is responsible to support the design, integration and testing to ensure CSRR and each of the PORs continued to meet their performance requirements. The lead systems engineer, also the systems architect, coordinates the efforts of the platform engineers to maintain the commonality of the CSRR design across all platforms while balancing the needs of the individual programs and platforms. The chief engineer in essence devotes much of his efforts to "herding the cats" toward a common goal. When interviewed the CSRR chief engineer (Mike Gozzo 2013 personal communication) defined his roles and responsibilities as follows:

1. Leading a team of engineers throughout all aspects of the systems engineering process. This includes:
2. Developing plans and processes to achieve the desired program goals and monitor progress towards those goals.
3. Collaborate with technical experts to outline the overall architecture and design of baseline modernization.
4. Be knowledgeable enough in all areas of the system to be able to discern important issues vice minor concerns or wants.
5. Constantly watch for feedback of failing or inadequate processes and implement course corrections.
6. Act as final decision for technical and non-technical issues as required. (Mike Gozzo 2013 personal communication)

The design agent works with the chief engineer who oversees the design team. The design team is composed of platform engineers who are supported by functional SMEs from other areas such as network systems, software, information assurance, integrated logistics, testing and evaluation and others. The SMEs from the other programs are available to provide information and expertise during the integration SOS activities. The challenge of working with other programs is identifying the appropriate definition point between what is entirely within a POR responsibility and what impacts the SOS as a whole. Each platform engineer is responsible for creating and tracking the baseline for

the version planned. These results are shared within the local design teams so maximize the sharing of information between the platform engineers. The results produce the information necessary to support installing a version of CSRR.

The chief engineer must have a vision of what the overall SOS is going to be in terms of capability, function, and physical design (Mike Gozzo 2013 personal communication). He describes these as

1. Understanding the inter-relationships of the subsystems and the components. These drive the end to end capabilities and determine if they can be achieved (Mike Gozzo 2013 personal communication).
2. Look at the functional block diagrams early in the process to determine if the proposed design blocks will work together? The next level looks beyond functionality of the interrelationships down to the physical and logical relationships (Mike Gozzo 2013 personal communication).

The CSRR program envisioned using an evolutionary approach for the development of each version. Each version would be developed based on the expected capabilities needed. Version zero replaced the legacy architecture and most of the components. Version one delivered improvements to RFDACS and the operator workstations. Version two provided improvements to network components and introduced SHF. Version three was originally planned to include JTRS and ADNS Increment three as the major capability drivers. As each version is created the work from the previous one is leveraged to maximize the open architecture and commonality in terms of hardware and software.

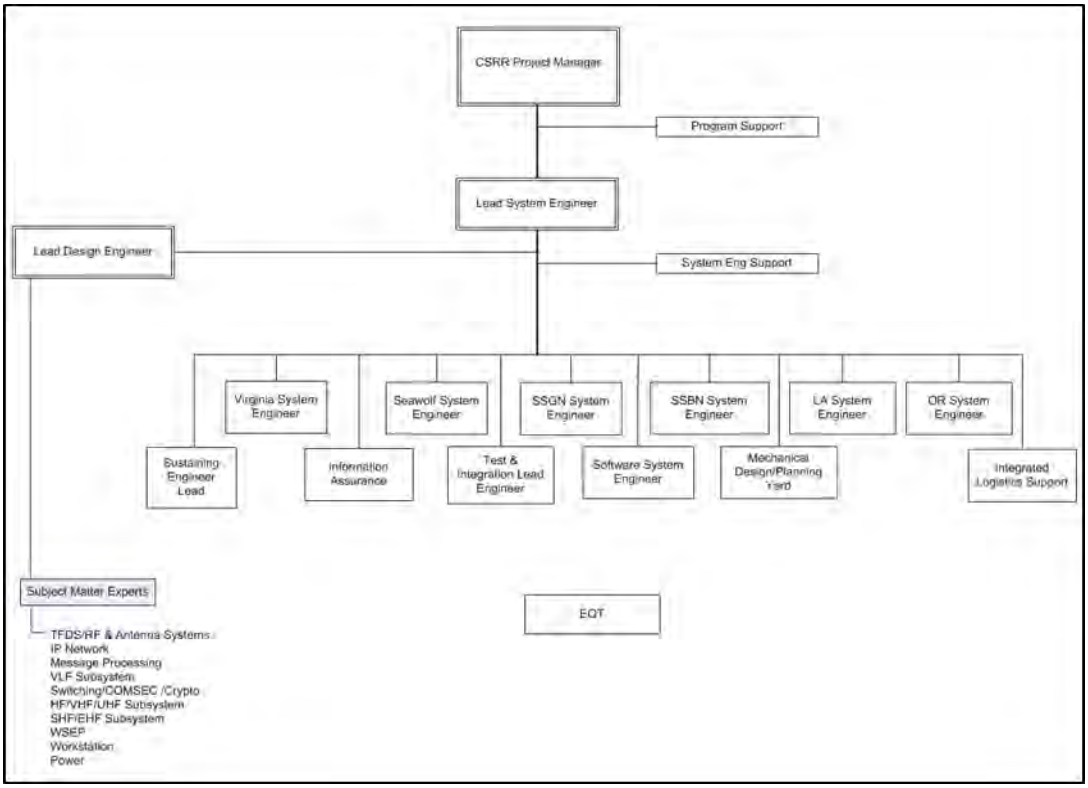

Figure 24. NUWC Design Team Organization (after Anderson 2014)

The challenge of developing a version lies with the expected maturity of the systems planned for integration (Steve Devin 2014, email questionnaire). Deployed systems are usually mature and may be difficult and expensive to change. Systems still in the early stages of development introduce added risk through additional changes arriving late in the development cycle. Attempting to use the SOS engineering and integration process to force maturation introduces potential rework and testing, and potential recertification which can impact cost, schedule and performance (Steve Devin 2014, email questionnaire). Finding the proper balance is a constant challenge for the lead systems engineer. Figure 25 (DAU 2013, 37; Dahmann et al 2011) reflects the SOS system engineers view to implementing an SOS. The wave model begins with each incremental change planned for the overall SOS. The wave model represents an iterative process to analyze, design, build, test and deploy an SOS. Common Submarine Radio Room has documented their process in a value stream analysis (VSA) which enables a great deal of repeatability.

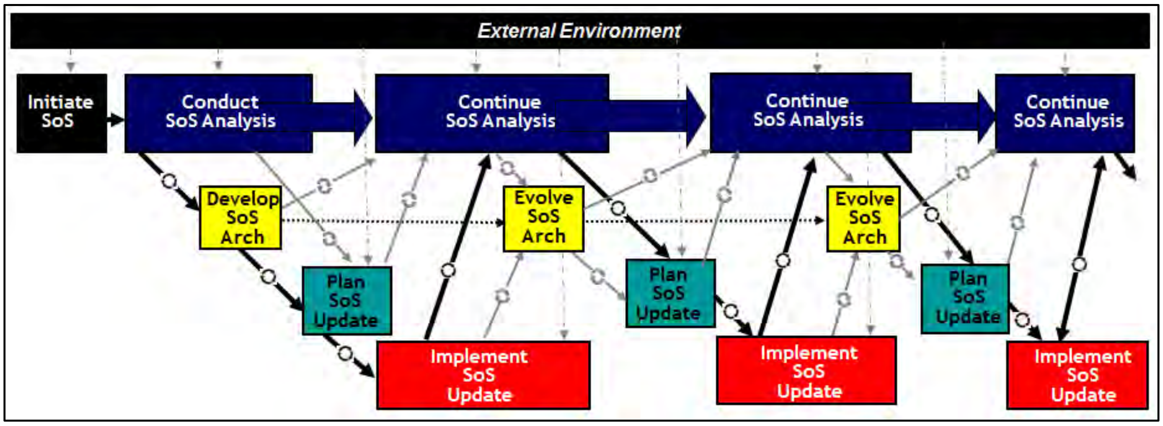

Figure 25. Application of the Wave model to CSRR

Application of the wave model to CSRR is performed in concert with the system engineering technical review (SETR) process from the acquisition guidance (DOD, 2013). Initiating the SOS design begins with the SOS analysis which, depending on the maturity of the proposed systems is normally an initial technical review or a PDR. The PDR outlines the functional baseline of the systems involved and assessing the proposed changes to the SOS baseline. Once the proposed changes are agreed upon detailed planning of the SOS update takes place and is reviewed again at the CDR. Approval at CDR establishes the physical architecture of the SOS leading to completion of the development, integration and certification of the SOS architecture. Following certification the SOS architecture will be implemented as an update. Further changes leverage the previous development cycle. This process occurs during the development of each version of CSRR as systems and capabilities are inserted and removed. This same process can be applied to other related SOS such as SWFTS, TBMCS, or a VA platform.

Enclosure three of interim DOD instruction 5000.02 *Operation of the Defense Acquisition System* (DOD 2013, 82) mandates the use of SE principles as part of the acquisition activities. The SETR process defines the mandatory and recommended activities that occur over a programs life cycle. The challenge with this is the SETR process was created to address a single program. The DOD instruction 5000.02 addresses SOS briefly in terms of establishing a special interest program, developing an acquisition strategy, identifying a lead systems integrator and testing. If a program happens to be a

directed SOS most of these activities are occurring as needed in the overall effort. Since many mission capabilities are the result of creating an acknowledged SOS the individual programs may be in different phases of their life cycle. The main challenge to the SOS engineer is coordinating the integration and implementation of changes to minimize potential negative impacts. DASN (RDT&E) drafted a revision three to the current *Naval System of Systems Engineering Guidebook* (ASN (RDA) 2006). The focus of the revision is described in the foreword of the draft

> The focus of this Guidebook is on the mission level System of Systems engineering process to provide needed capabilities and functionality within a Net Centric Operations and Warfare environment in support of a Mission Area Capability. It provides a guide to recommended processes, methods and tools that, when applied by the Mission Area Systems Engineers, will aid program managers, their SEIPTs, support teams, and contractors in producing systems that successfully deliver the Mission Area capability. (DASN (RDT&E) 2013)

Revision three significantly revises the content but the end goal of delivering mission capability from a SOS context is preserved. An important distinction in revision three is how a SOS is redefined in the context of mission capability. The following quote from the background captures this new definition and intent.

> In the future, global operations will be conducted by distributed, integrated and interoperable forces. This future warfare is about capability delivered by a "SOS" operating as a single system. SOS is defined in this document as a force package of interoperable platforms and nodes acting as a single system to achieve a mission capability, i.e. a mission level SOS. Typical characteristics include a high degree of collaboration and coordination, flexible addition or removal of component systems, and a net-centric architecture. The capabilities provided by each constituent system operating within the SOS are framed by the integrated force package architecture. (DASN (RDT&E) 2013, 6)

In order to achieve these capabilities the SETR processes must be applied at each level (e.g., the CSRR SOS must support the platform and mission level SOS). The PORs supporting CSRR follow the SETR processes as part of their development cycle. The level of complexity and amount of change within each system and the maturity of the program can determine which SETR events may be included or omitted. A SOS will be using an iterative process previously described and may include events such as an initial

technical review, systems requirements review, or software specification reviews. The CSRR value stream analysis identified the following SETR events in Table 18 which occur during the design and development phase. The SETR events are not the main goals within a program development cycle but status reviews assessing the maturity of a system or SOS to progress to the next phase.

From a SOS approach each individual system performs these SETR events as well. These POR SETR events are important to the SOS since they drive maturity and demonstrate they are ready to be implemented in the overall architecture. The design-build approach at both the systems level and the SOS level in concert with the SETR events attempt to minimize the risks of introducing a capability before it is ready.

Table 18. System Engineering Events Occurring During Design and Development

Event	Activity
Preliminary Design Review (PDR)	The PDR provides the initial review of the design at the functional level. At this point individual systems maturity is still low, approximately 20–30 percent.
Integrated Baseline Review (IBR)	The IBR follows the PDR to establish the development baseline. Each development baseline is based on a Lean Six Sigma (LSS) Value Stream Analysis (VSA) which identified the major events and the time required to accomplish them. The VSA uses an accordion concept allowing each version development baseline to expand or shrink based on the expected amount of work. Once the development baseline is approved it provides the main tracking method to assess if schedule was being maintained.
Critical Design Review (CDR)	CDR is scheduled to occur when the design maturity is estimated to be approximately 85–90 percent. At this point the physical design is presented along with proposed testing criteria and assessments from the production, ILS and IA leads. Systems that are not determined to be mature by CDR are recommended for deferral to the next version.

2. Testing and Certification

CSRR follows a build-test-certify approach during the development cycle as a risk reduction methodology. Once a component or system is received the CSRR team performs several levels of testing prior to deployment to the fleet. The goal is to minimize repeating any testing performed by the parent POR while ensuring it will fit and function within the CSRR architecture and will be interoperable. Figure 26 illustrates the systems which undergo some level of testing within the overall system of systems.

With the exception of functional interface testing and regression testing a test readiness review will occur to get concurrence from the principal assistant program manager (PAPM) or program manage the CSRR is ready to begin testing. The levels of testing are described below. Once the testing is complete the results are shared with the stakeholders as necessary to support meeting program acquisition milestones.

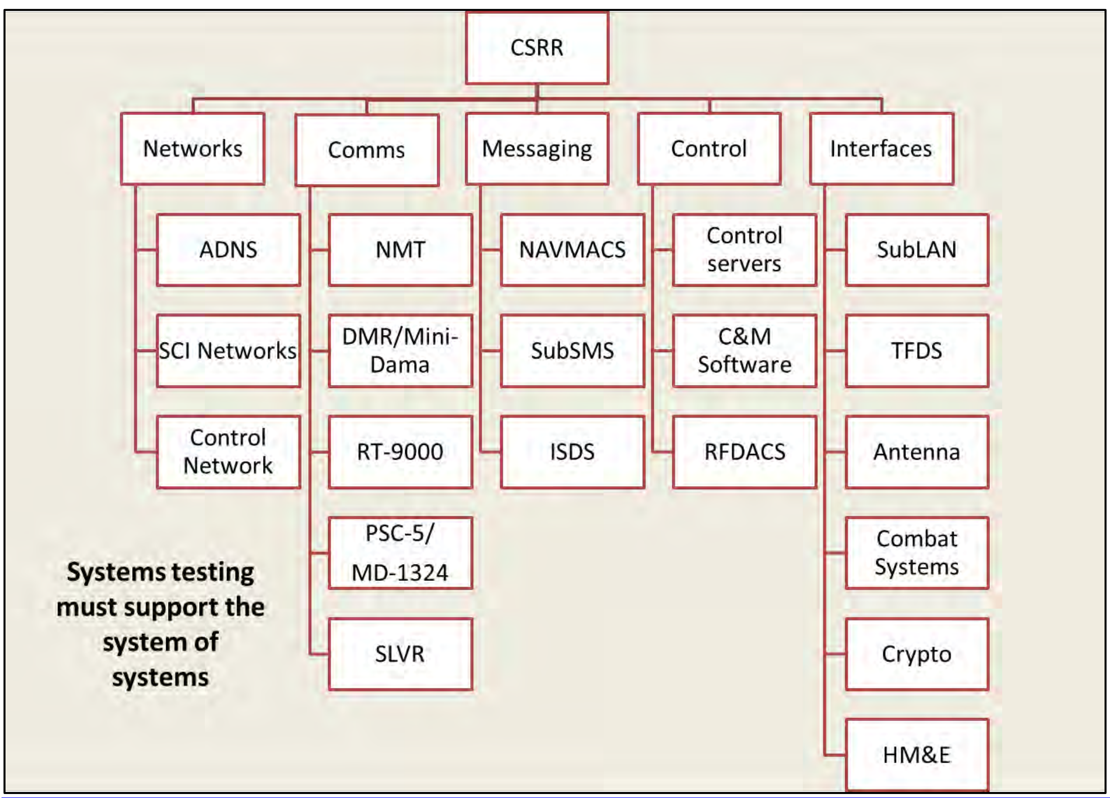

Figure 26. Systems Testing Required in Support of Common Submarine Radio Room as a System of Systems

a. Functional Interface Testing

This is the first time the system or component can be actually evaluated by the design team. The system is evaluated for form and fit, logical and power interfaces are checked, and the system documentation is reviewed. Accomplishment of this testing is under the direction of the design agent and chief systems engineer. Once this is complete, the system or component is reported at the CDR as ready to support SDVT.

b. System Design Verification Testing

SDVT is a formal test event to validate the system will operate within the CSRR architecture using an end to end environment, will meet its own system requirements, and will not degrade the CSRR performance specifications defined in the SUBECS CPD. When the system is ready to enter SDVT the design agent and test and evaluation lead will brief the PAPM and request concurrence to begin testing. Once the system has successfully completed SDVT, the physical design has been fully verified and validated. If necessary any regression testing required will occur after SDVT. If this is a first of version design, the CSRR will proceed into SAT.

c. Systems Acceptance Testing

Systems acceptance testing is performed if the design is a first of version or has been determined necessary by the program team. Systems acceptance testing is the final performance run to demonstrate system stability while operating during a series of scenarios. Operating procedures are validated using fleet operators and system configuration information is collected to support development of the CSRR Multi-Reconfigurable Training System (MRTS). If necessary any strategic certification testing will occur as well as collecting equipment data to determine operational availability (A_o). Testing is accomplished using operational circuits with the submarine BCA. Authority to proceed into SAT is granted by the PMW770 program manager at the SAT test readiness review.

d. *Regression Testing*

Any deficiencies or changes that occur during SDVT or SAT require some level of retest to verify if a patch or configuration change works. Regression testing is not considered a required event but enough time is normally scheduled between SDVT and SAT testing of any changes.

e. *Cybersecurity Testing*

Cybersecurity (or IA) testing will take place in concert with the formal testing events and as necessary in between testing events to verify security technical implementation guides are applied and validate they are working. Any updates that need to be installed will be accomplished prior to SDVT and SAT.

f. *Strategic Certification Testing*

Strategic testing is required by the Joint Staff to ensure any changes to a NC3 system have been properly and adequately verified and validated prior to deployment to an operational NC3 activity or platform. The primary certification tests are TCM and EAM certification.

1. TCM Certification—TCM certification is accomplished to validate any hardware or software changes made to the messaging path by transmitting a predetermined number of targeting messages and recording them to media. An agent for SSP analyzes the messages to verify they are fully readable by the strategic weapons system. Any discrepancies are analyzed and corrected before issuing the final certification recommendation to U.S. Strategic Command.
2. EAM Certification—Clear and concise communications between the president and strategic forces requires the use of highly reliable communications paths. In accordance with JCS direction any changes to systems impacting the messaging paths are tested prior to being fielded. The certification is an end to end test to verify any changes have not impacted the reliable delivery of EAMs. Testing results are provided to the JCS for review and approval.

The design and development process maintains the rigor necessary to ensure any issues or deficiencies are resolved or mitigated before deployment in an operational environment. The challenge from the system versus SOS perspectives is defining what the right level of design, development and testing that must be done. The design and

development activities are largely driven by physical and functional characteristics of each system. Testing becomes a more contentious issue at times, especially if the POR feels they have performed an adequate level of testing to demonstrate they are ready for fielding. History within DOD is replete with examples where this argument has been proven false. TBMCS is one example where unclear requirements and over reliance on the contractor led to being unable to validate or verify the operational readiness prior to deployment (Collens and Krause 2005, v, 27–37). The Hubble space telescope is another where the system was launched into orbit before a flaw in the main mirror was detected. The repair required an unplanned 11 day space mission by the shuttle *Endeavor* (Mattice 2003, 10). The F-111 attempted to implement concurrency of design validation and verification while entering production. The validation and verification resulted in several costly design changes to 200 aircraft and schedule delays due to structural failures which grounded the entire F-111 fleet for several months (Richey 2005, 24). While it can be extremely challenging to test every possible scenario the testing approach from the system to the SOS should follow a logical progression to maintain traceability and identify potential areas of risk to investigate further. It is incumbent on the SOS program manager to keep the stakeholders aware of the status and concerns of any shortfalls in the testing. Vaneman and Budka (2013) illustrated the role of SOSE integration in Figure 27. Each POR performs the activities shown in the lower portion of the Vee. If these are not adequately performed or incomplete, the validation and verification necessary for certification, deployment and sustainment, shown in Figure 28, increase the risk of failure. This approach is also reflected in table A-6 of annex A in the SE Guide for SOS (Director, Systems and Software Engineering 2008, 103) of the importance of the SOS verification building on the efforts of the individual systems. Once the CSRR version has completed the design and development phase, responsibility for procuring the materials and equipment shifts to the production agent.

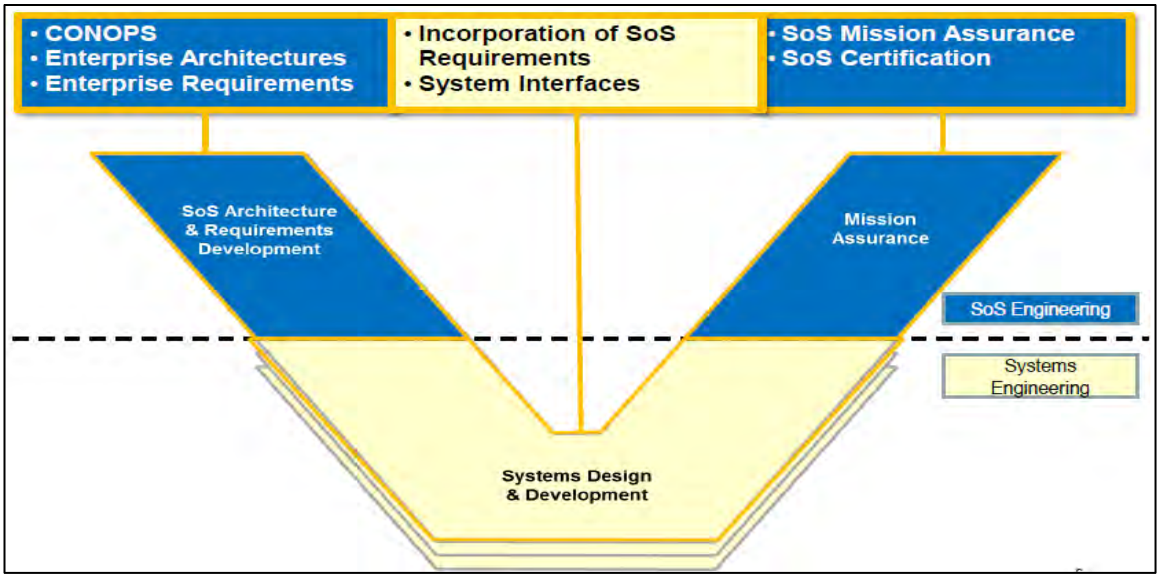

Figure 27. System of Systems Engineering and Integrations Role in System Design and Development (from Vaneman and Budka 2013, 6)

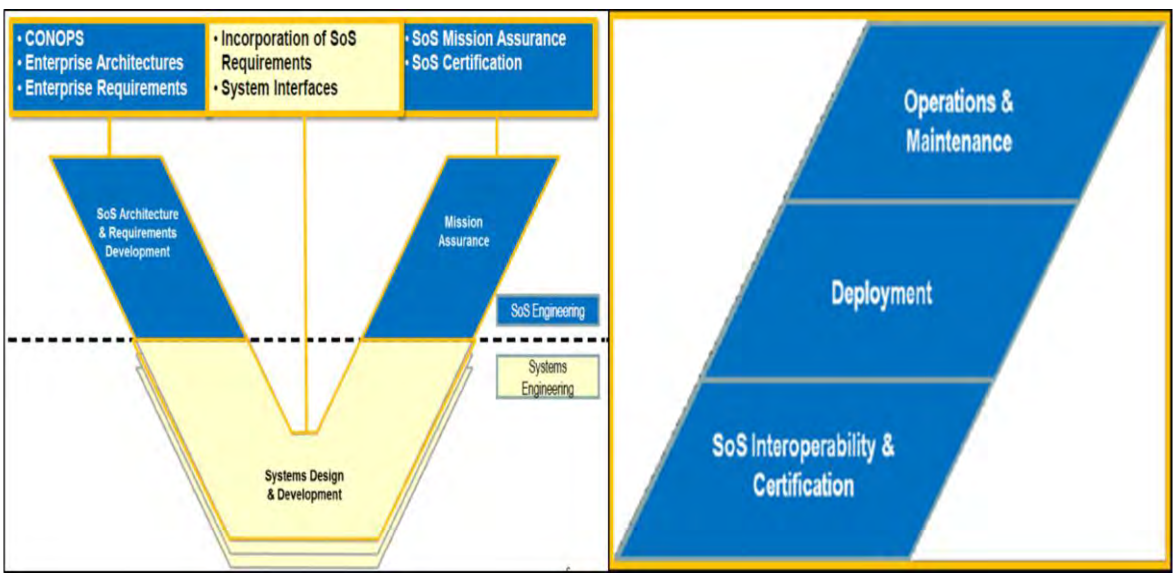

Figure 28. Validation and Verification Supporting the System of Systems Interoperability, Deployment and Sustainment (after Vaneman and Budka 2013, 6, 11)

The design agent also manages responsibilities as the CSRR planning yard to maintain configuration control of each CSRR version. The purpose of the planning yard is to serve as the repository for all drawings concerning CSRR. The CSRR planning yard maintains a partnership with the platform planning yards to manage changes that occur

within the CSRR boundary and the platform boundaries. Changes are managed via a planning yard liaison action request (PLAR) between the design, production and installation teams. Any changes that occur post testing will be assessed to determine the impact and if any additional design or testing is required.

C. COMMON SUBMARINE RADIO ROOM SYSTEM OF SYSTEMS PRODUCTION APPROACH

Prior to CSRR, SCSS modernization involved the coordination of multiple programs to build and ship their own installation kits. This meant the alteration installation team had to verify they had all of the right materials and equipment and develop their own integrated drawings to accomplish the installation. Lack of standardization between the organizations and programs created a significant amount of variation of what a kit would contain. This approach also created complications if several install kits were managed by different installation teams. The lack of coordination added complexity in a very dynamic, fully scheduled availability. This approach also created a substantial amount of rework if errors were found in a ship alt package or no guidance was provided for configuration issues. Ultimately, this approach ended up creating 48 similar yet different configurations among the LA platforms. This same approach has also resulted in creating different configurations among the several hundred surface platforms as well.

The SSC LANT production agent was interviewed as part of this research via email and telephone. SSC LANT oversees production activities to include procurement of all equipment and materials necessary to support a CSRR installation, PITCO, kitting, and shipment to the site (Dave Bednarczyk telephone interview 2014). By leveraging opportunities for quantity purchases of installation materials, significant cost savings can be realized. Individual PORs provide their equipment and any unique materials necessary for inclusion in the installation kit. The production team shown in Figure 29 engages with the various PORs as necessary to coordinate the procurement or delivery of their equipment and materials for PITCO and shipping to the installation team. The production team assigned responsibilities by platform to address specific issues while balancing workloads. The PITCO period allows pre-loading and configuring software and

hardware. Additionally it serves as a burn in period to eliminate possible failures prior to shipping. Once PITCO is complete, the installation kit is packed and shipped to the installation site. Similar to the design agent's role in performing SOS verification, PITCO provides the overarching testing to ensure the product shipped to the site is operational. This production quality assurance approach mitigates the risk of failures occurring during the production and systems operational verification testing (SOVT) (Dave Bednarczyk telephone interview 2014).

The PITCO process successfully demonstrated for V1 and V2 proved to be more difficult to perform for V3. Some PORs chose to ship their systems directly to the installation team while others sent them to SSC LANT without their final configuration settings inserted. Having some incomplete components and others not available impacted the ability to perform a complete PITCO and validate the ship set prior to packing and shipping.

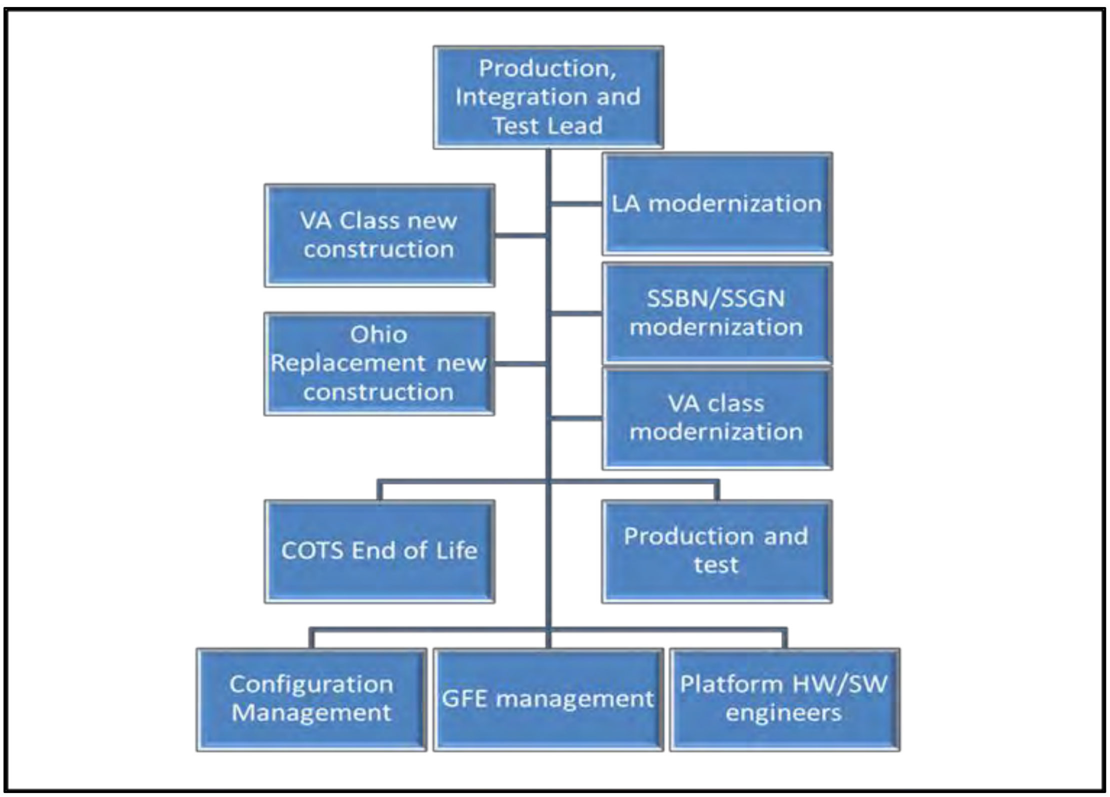

Figure 29. CSRR Production and Support Team

Late changes to software and hardware configurations also caused delays. The initial V3 ship set installed on the USS *Hampton* did not perform PITCO which resulted in a number of failures caught by the installation and SOVT teams. Failed parts had to be replaced from the CSRR production team and the other programs. These failures in turn drove up installation costs and delayed schedules. Data collected from follow on installations by the production agent confirmed failure to accomplish a PITCO continued to drive costs upwards of several hundred thousand dollars and delay completion from days to weeks (Dave Bednarczyk telephone interview).

Previous to the deployment of V3 the production team procured and managed all of the system components necessary to install CSRR. As the procurement arm for the CSRR program SSC LANT was able to control their fate by purchasing or designing the materials necessary to build a ship set (Dave Bednarczyk telephone interview). The advantage of this approach is production and kitting responsibilities solely resided with the production agent. The disadvantage of this is systems normally managed by another program office used a different configuration and could not easily assume responsibility of these new components within their budgets. Specific components, such as the EHF Follow on Terminal, was provided from PMW 170. Others had to be designed entirely to fulfill requirements if a formal POR was not available. One component which was entirely built to support CSRR was the modern legacy cryptographic system (MLCS) which was originally planned as a replacement for the multifunctional cryptographic system (MCS). The vendor's inability to prove the viability of the MCS resulted in its cancellation in 2004. In order to keep the CSRR program on track an alternate solution was rapidly developed and deployed with version zero. The MLCS was created in less than a year to provide the similar capabilities as the MCS. Created only as a stopgap solution, the MLCS is being replaced with a POR crypto universal enclosure managed by PMW130.

Version three shifted to an approach of using consolidated engineering changes (EC) and ship alteration record (SAR) with the ship installation drawings (SID) contained in an associated EC creating what was called a "SIDless SAR." The creation of the ECs and their associated SARs were used to create the consolidated list of bill of materials the

production team would provide and a list the installing activity would have to provide. This approach identified a number of issues when engaging with other PORs. For V3, PORs were expected to provide their equipment and either the installation materials or funding to procure them. This approach added another layer of coordination which caused confusion, resulting in equipment received with the wrong configurations, damaged, or shipped late. As a build to print organization, introducing late changes to the SSC LANT production team caused perturbations in costs and schedules due to rework (Dave Bednarczyk telephone interview). PLARs directing changes to cables or mounting kits often meant pulling materials out of a packed kit, creating a risk of something being misplaced. This process is reflective of an acknowledged SOS characteristic where the SOS has objectives, resources and manager but must also collaborate with the constituent systems (Director, Systems and Software Engineering 2008, 5).

D. COMMON SUBMARINE RADIO ROOM SYSTEM OF SYSTEMS INSTALLATION APPROACH

Common Submarine Radio Room installations are performed by alteration installation teams (AIT) contracted through the SPAWAR Systems Center Installation Management Office (IMO). In 2011, the FRD was established to provide a single agent responsible for coordinating installations. The platform installation manager (PIM) is the embedded FRD representative within the Undersea Integration program office responsible for coordinating installations. The PIM works with the respective product program offices to ensure the equipment, materials and personnel are available to support the installation.

The installation packages developed by the design agent included the bill of materials needed to accomplish the work. The intent was to have the POR fund their share and leverage the advantages of making quantity purchases. This effort resulted in an agreement between PMW770 and several program offices in which the CSRR program would purchase the materials and deliver them in the kit. The other PORs installation funding would be used first and then CSRR installation funding would be used.

Each installation is assigned government onsite installation coordinator (OSIC) to serve as the liaison between the platform, the local maintenance activities, and the installation team. The OSIC is responsible for arranging for the modernization, testing, and training activities. Once the production phase of the installation is complete the SOVT is performed. A SOVT is performed by government personnel and serves as the acceptance testing. Since SSC LANT had more collective experience with CSRR they provided the majority of the SOVT SMEs. The production agent provides support to the installation teams if a piece of material or equipment fails or is defective. Once SOVT is complete the platform assumes responsibility for CSRR and all of the ancillary systems.

E. COMMON SUBMARINE RADIO ROOM SYSTEM OF SYSTEMS SUSTAINMENT APPROACH

Even though CSRR is a SOS there are sustainment responsibilities to be maintained. SPAWAR Systems Center Atlantic is assigned as the CSRR in service engineering activity (ISEA) responsibilities. The ISEA shown in Figure 30 is responsible for providing onsite and distance technical support, provides the initial spares outfitting, and is the CSRR inventory control point for repair parts. The ISEA maintains a cadre of onsite representatives (OSR) at most submarine ports which provide local support and perform minor modernization. The production agent is responsible for overseeing the activities of the ISEA and was interviewed as part of the research. Notes from the integrated logistics support management team, fleet support team and program management review action items were reviewed as part of this research. Obsolescence management is a recurring item which must be managed by the ISEA working in concert with the support activities of the other PORs.

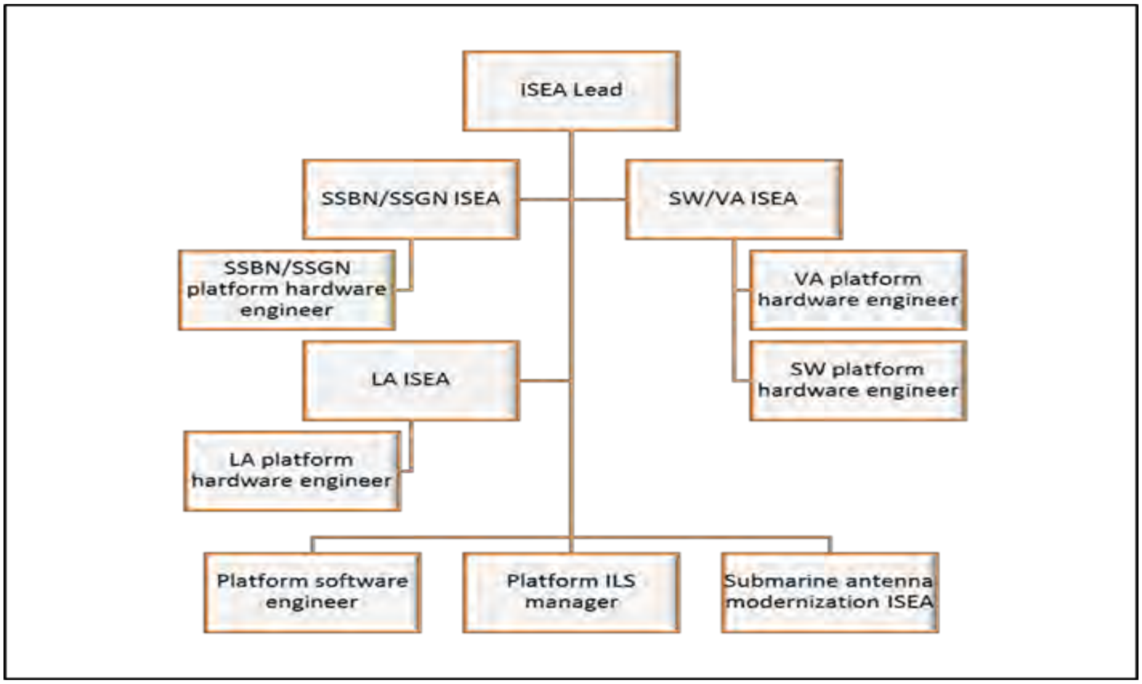

Figure 30. SPAWAR Systems Center Atlantic In Service Engineering Activity Organization

Unlike Trident IRR, which saw little change until the introduction of submarine IP, both SCSS and CSRR went through a significant amount of change as systems became more tightly integrated and automated. The SCSS represented a transition from manual patch panels to the automated baseband switching eliminating the manual patching of crypto devices to other baseband equipment and consolidating a number of individual systems into a consolidated modernization availability. Common Submarine Radio Room introduced an integrated yet open architecture which automated RF switching and expanded the network to control the systems and distribute information to the appropriate users.

Introduction of new changes normally results in an increase in requests for technical assistance until enough native user knowledge is available to operate and maintain their systems. One drawback of installing a new system is the lack of technical expertise of how the system interfaces with other systems. The OSRs are responsible for accomplishing minor modernization and providing onsite technical assistance to develop the core of knowledge so users can determine if a problem is the new system or

elsewhere. The OSR can assess a problem to determine if it is CSRR related or caused by an individual system and if necessary engage the specific POR SMEs to resolve the issue.

F. COMMON SUBMARINE RADIO ROOM SYSTEM OF SYSTEMS TRAINING APPROACH

SSC LANT is responsible for developing the training material used by Submarine Learning Center on their multi reconfigurable training system (MRTS). The MRTS is a complete network based training system which provides a virtual representation of the CSRR using touch screen technology mounted in full sized racks representing a CSRR system. Prior to MRTS CSRR training was provided using training technical equipment (TTE) which is a physical and functional representative ship system installed in a training laboratory. The advantage of this obviously is the ability of the operator to touch and manipulate the systems just as they would on the platform. The disadvantage of using TTE is

1. If the TTE breaks down, training value can be lost.
2. In order to replicate this capability, it must be installed at each site or operators must travel to the site for training
3. There is a significant cost to install and maintain TTE. This includes a cost on the program to procure additional assets increasing their TOC.
4. Pre faulted modules and scenarios had to be developed. Occasionally introducing a fault could actually cause a real failure.

Notes from the submarine communications and networks training management team (SCANTMT) were reviewed as part of the research. A significant challenge which confronts the training community concerns the delivery of training for a system of systems. The CSRR training uses a system of systems approach for operations and maintenance while each individual program provides their own training solution and ILS documentation. The submarine force has recognized the value of using a trainer like MRTS and is implementing similar approaches for other system trainers including weapons control and electronic warfare. Unfortunately, the lack of a concrete common requirement within the system training plans has resulted in training solutions which do not synchronize well.

The SSC LANT training team is partnered with the NUWC ILS team which uses the CSRR documentation and information from the individual programs to incorporate their systems information into the MRTS. There are several advantages of using a SOS solution like MRTS

1. While a loss of a MRTS at a school site can impact training, the chance of entirely stopping training is substantially reduced since each training site has several systems installed.
2. The ability to replicate the training capability has a non-recurring cost to install the hardware and software. Once this is complete, updates will be developed by the MRTS team and distributed to all sites.
3. Removing the TTE eliminates the cost of installing a new trainer and associated maintenance and modernization costs.
4. The ability to reconfigure the trainer from one CSRR version to another can be accomplished in very little time.
5. The MRTS allows an operator to still manipulate his CSRR and get the applicable responses. This includes training in various mission scenarios and equipment casualties.

The CSRR shares several characteristics with the Air Force KC-135 FTS. The KC-135 FTS uses a hardware TTE approach to train flight crews (Chislaghi, Dyer and Free 2010). Their approach shared the same challenges as the TTE installed at the training facilities in Bangor, Washington and Kings Bay, Georgia. The Air Force discovered like CSRR that resources had to be allocated in order to maintain and upgrade the trainers. The approach at this point treated the trainers like platforms for modernization purposes. This approach was feasible as long as changes were minimized. However, the rapid modernization occurring across the fleet forced acknowledgement this approach was no longer cost effective nor responsive enough to meet the fleet operator needs. The transition to MRTS demonstrated a SOS training approach could be effectively developed. The success of the MRTS program resulted in the submarine force expanding its use to other systems.

G. CSRR SOFTWARE DEVELOPMENT AND SUSTAINMENT

SSC PAC is responsible for the development and sustainment of the control and management (C&M) software. The software project manager works with the prime

vendor to develop new updates for each CSRR version via delivery orders. All other programs provide their own software to support their systems but also provide information for enabling remote operation of their systems from the C&M. The C&M software provides the overall systems control and management of CSRR. The integration of new capabilities identified from information derived from the constituent programs to create the necessary drivers. The advantage of this approach means the individual programs maintain their own software and the C&M provides the overall capability of tying the individual components to each other, in essence is the glue needed to make everything work efficiently.

The challenge of managing the C&M software is similar to other programs. Changing technology, new interfaces, and increasing security upgrades via software while leveraging deployed applications is a challenge for a single program. This challenge is no less for the C&M which must handle a multitude of components for configuration, circuit management and system status.

H. CHALLENGES FACING COMMON SUBMARINE RADIO ROOM AS A SYSTEM OF SYSTEMS

The challenges facing CSRR or any other SOS share many characteristics. As an acknowledged SOS the CSRR program manager has the same responsibilities as his peers managing their product programs. The SOS program manager faces additional challenges to ensure the specific program activities under his responsibility take into account not only his program but the challenges and opportunities of his peers. If a program attempts seeks to optimize their constituent system without consideration of the impact it may have on others the results may be a more fragile system, vulnerable to intentional or unintentional degradation.

1. Program and Other POR Requirements

One of the main challenges facing CSRR is the relationship it has with other programs. DOD largely acquires individual systems and integrates them versus integrating capabilities into systems of systems upfront. A notable exception was the GPS program which integrated several segments or components to deliver capability under the

lead of one service. Since GPS is classified as an ACAT I program, it was provided the authority to define the overall SOS architecture and the overall system requirements. GPS can be classified as a directed SOS since it was built to address a specific purpose, precise navigation and timing. The other services can develop their systems to accommodate their specific needs but must still be interoperable within the established GPS architecture. The JCIDS approach was implemented in 2002 to address shortfalls in the DOD acquisition system. JCIDS introduced a more defined process of identifying capability gaps and solutions. However, this did not specifically address how capabilities could be delivered via a SOS. DOD did recognize certain capabilities required the integration of several systems to create a SOS. Most of these were acknowledged SOS intended to work together but the emphasis on the system from a budgetary perspective shifted the focus off the SOS and onto the system. CSRR faces this same challenge. While it is an ACAT II program, resource officers considered it a system like many others. This view often results in creating breaks among the various constituent systems and the overall SOS.

CSRR can be considered an acknowledged SOS which has its own recognized requirements and objectives, but each of the constituent programs is independently managed, funded, and sustained. SWFTS is under the cognizance of PEO SUB and is not a formal program, but a managed agreement which shares many characteristics of a directed SOS. The challenge is CSRR is classified as an ACAT II program responsible for delivering a defined capability like other program when viewed from the resource sponsor level. Budget, contractual or technical changes affecting individual programs within PEO C4I or PEO SUB can impact the overall C4I capability and potentially force significant design changes to the CSRR architecture (Darlene Sullivan 2014, email response to questionnaire). Additional non-technical issues can occur when there is a turnover of personnel. These new personnel sometimes require an introduction to reinforce the "value added" the system of systems approach such as CSRR provides (Darlene Sullivan 2014, email response to questionnaire).

A persistent challenge encountered with the extensive use of COTS or new technology has been the late delivery of equipment, or if received, it has not been fully

tested (Steve Devin 2014, email response to questionnaire). Some of this is attributable to poor communication, technical or programmatic issues (Darlene Sullivan 2014, email response to questionnaire). One example is the joint tactical radio system (JTRS) airborne maritime fixed station (AMF), an ACAT I program. JTRS-AMF was envisioned to be the common replacement for the different radios procured by each service. The CSRR V3 design planned using JTRS-AMF as a cornerstone component. The inability to meet milestones, de-scoping of key requirements and cost overruns ultimately caused the program to be cancelled. The cancellation forced the program plans and schedules for CSRR and other programs to be revised, and last minute investigation into other solutions to provide the capabilities to the warfighter was pursued. Similar issues have been encountered as other systems failed to meet their schedules or had funding cut from their program.

Testing of a SOS poses a number of challenges to validate and verify capabilities. Testing of individual systems can be performed using clearly defined criteria in a controlled environment. Even these events are solely focused on demonstrating the specific capabilities inherent to the system. Testing and evaluation of a SOS is more difficult since the aggregation of individual requirements can result in a testing event which may be very difficult or expensive to accomplish. Common Submarine Radio Room has performance requirements defined in the CSRR CPD and SUBECS CRD, but these must be adjudicated against the individual systems to eliminate conflicts.

End to end testing may also identify a problem which was not evident during systems testing. This emergence may force unexpected changes to a specific system or a group of systems. An acknowledged SOS, made up of individual PORs, must come to agreement about testing approaches and scope. Each system performs testing to meet their particular key performance parameters and key systems attributes. Testing a system rarely involves evaluating full end to end performance except as part of a formal developmental test (DT) or operational test (OT) event. The aspects of a SOS from stakeholder involvement to performance and behavior have implications on the testing and evaluation of a SOS. Table 19 lists the aspects of a system and acknowledged SOS to identify implications for SOS testing and evaluation (Dahmann, et al. 2010). The CSRR

DT and OT approach used for each version had to take a macro level view to demonstrate it could meet the CPD requirements. Any problems noted in individual systems had to be addressed since these reflected against the overall operational effectiveness and suitability. Using a systems approach would not have identified many of the issues during DT and OT.

2. Integrated Logistics

Another challenge is the myriad of integrated logistics support (ILS) issues which arise from managing a SOS. Acknowledged SOS architectures require close cooperation among the different programs to ensure documentation, repair parts and intermediate or depot support in place at the right locations and formats. Each version performs a reliability assessment to determine the appropriate quantity of spare parts to carry. The type of reliability analysis performed is determined by the type of platform. SSBNs perform a mission essential component (MEC) analysis which assigns a numerical value. A higher number represents a more critical part. This reliability analysis identifies which repair parts must be onboard the SSBN to support the strategic deterrence mission. All other platforms perform a readiness based sparing (RBS) analysis. Like the MEC an RBS performs a similar function to determine which repair parts should be onboard.

Each system performs their own reliability analysis which can result in different sparing levels when the analysis is performed at the SOS level. System maturity can impact the accuracy of the sparing analysis. New systems are analyzed using predicted or vendor provided data. Deployed systems can use actual failure data. Any disparities between the systems reliability analysis and the SOS analysis must be resolved, especially if a spare part is determined to have a high MEC, or additional spare parts are needed to meet the results of the overall SOS. A high MEC determines more repair parts are required, which in turn drives cost. Conversely, if the systems within the SOS share the same components the overall sparing quantities may be reduced.

Table 19. System of Systems Test and Evaluation Implications (from Dahmann et al. 2010)

Aspect	System	Acknowledged System of Systems	SOS T&E Implications
Management & Oversight			
Stakeholder Involvement	Clearer set of stakeholders and aligned objectives	Stakeholders at both system level and SOS levels (including the system owners), with competing interests and priorities; in some cases, the system stakeholder has no vested interest in the SOS; all stakeholders may not be recognized.	Validation criteria more difficult to establish
Governance	Aligned PM and funding	Added levels of complexity due to management and funding for both the SOS and individual systems; SOS does not have authority over all the systems.	Can not explicitly impose SOS conditions on system T&E
Operational Environment			
Operational Focus	Designed and developed to meet operational objectives	Called upon to meet a set of operational objectives using systems whose objectives may or may not align with the SOS objectives.	System level operational objectives may not have clear analog in SOS conditions that need T&E
Implementation			
Acquisition	Aligned to ACAT Milestones, documented requirements, SE	Added complexity due to multiple system lifecycles across acquisition programs, involving legacy systems, systems under development, new developments, and technology insertion; Typically have stated capability objectives upfront which may need to be translated into formal requirements.	Depends on testing of constituent systems to SOS requirements as well as SOS level testing
Test & Evaluation	Test and evaluation of the system is generally possible	Testing is more challenging due to the difficulty of synchronizing across multiple systems" life cycles; given the complexity of all the moving parts and potential for unintended consequences	Difficult to bring multiple systems together for T&E in synchrony with capability evolution.
Engineering & Design Considerations			
Boundaries and Interfaces	Focuses on boundaries and interfaces for the single system	Focus on identifying the systems that contribute to the SOS objectives and enabling the flow of data, control and functionality across the SOS while balancing needs of the systems.	Additional test points needed to confirm behavior
Performance & Behavior	Performance of the system to meet specified objectives	Performance across the SOS that satisfies SOS user capability needs while balancing needs of the systems	Increased subjectivity in assessing behavior, given challenges of system alignment.

Legacy or non-COTS systems, which may have spare parts in short supply, add new dimensions as well. The challenge to building or modernizing a SOS with a legacy system may determine additional repair parts are needed, only to find out there are no spare parts available, or the reengineering costs exceeds the available resources.

Documentation must remain current as well for each platforms configuration. This is one area where there is significant weakness. Individual systems will update their operating procedures, maintenance manuals and software user manuals as changes occur. The format of these manuals may vary as well unless the standards are included as a data item in the contract. Few SOS create overarching manuals which aggregate the information needed to create consolidated operating procedures. The IRR developed integrated procedures and manuals, providing a standard approach for CSRR which is used today. Overarching technical manuals, such as cable manuals, are created as references to support maintenance and repairs. The quality of overarching documentation is directly related to the quality of the source data. If the data is poor, extra work may be required to improve the quality.

3. Training

System of systems training is a relatively new concept for DOD. The approach used by CSRR is a large step in the right direction but the solution is imperfect. Effective systems engineering considers every facet to ensure they develop an appropriate solution. The SOS engineer must consider how the training solution impacts the desired end state. If there is little need to an operator to interface extensively with the system or there is a large cadre of onsite technicians the training solution may be minimal. If there is a need to train operators to respond to a complex scenario involving extensive C4I capabilities such as carrier strike group performing strike operations in concert with a cyber-operation or humanitarian aid / disaster relief the current trainers cannot be networked to support this and coordinating operational assets is time consuming and costly. A SOS engineer has the task of examining the SOS architecture to come up with a balanced approach to the solution.

To date there is little to no policy or guidance for managing the training of multiple systems integrated together. Each system is required to develop a training systems plan which is typically not coordinated with other systems. This in turn results in training materials and curricula to operate and maintain the specific AN/USQ-XX but little is covered about how it fits into the larger SOS architecture. A training course for a

technician may train them on a variety of equipment but there is very little about how they are related at a larger level. One limitation to this is the cost to build a SOS trainer is very cost prohibitive and the student throughput is limited to a predetermined number for each course. An option to meet this need is to build a virtual type trainer.

To meet this need the CSRR program developed a Multi-Reconfigurable Training System (MRTS). The MRTS is a virtual representation of the CSRR which is used to train operators and maintenance technicians. The system is composed of touch screen monitors mounted in the racks similar to the platform and arranged to match the platform configuration. The MRTS software emulates the real equipment and is loaded with a comprehensive suite of scenarios. Several advantages of this approach include:

- Lower costs to develop and update the trainer. The initial startup costs cover the hardware and initial software load. Installing a complete suite of technical training equipment (TTE) can cost $20 million and about $500 thousand annually for maintenance. Procuring and installing a MRTS is less than $1 million. Updates can be created once and deployed to all sites. Software development costs may vary but are still significantly less than hardware modernization and sustainment.
- The MRTS can be updated quickly via a software load. Hardware updates occur only as needed to address obsolescence issues. TTE remains in a static condition until it is modernized. Once TTE is modernized it cannot support earlier configurations for training.
- If necessary a MRTS lab can be reconfigured to a different version or version represented on another platform. Other PORs such as ADNS, SUBLAN, CANES and team trainers can leverage the MRTS approach. A TTE laboratory is limited to the installed configuration.

Increasing information assurance and cybersecurity requirements consume a larger role of training technicians and operators. The approach used today by the submarine force to address communications and networks is under the responsibility of two different ratings. Communications systems operations and maintenance is the responsibility of the submarine communications electronics technicians (ETR). All network responsibilities are managed by the submarine information systems technician (ITS). Current DOD policy mandates all personnel assigned duties to work on a network must be a certified member of the information assurance workforce (IAWF). This mandate did not discriminate between closed and open networks. The mandate created a

substantial amount of confusion for the technical ratings in terms of where the line of separation is defined between isolated networks used for the control of systems and those responsible for managing the flow of data from one point to another.

The duties of many of these technical rates mean they must have a substantial level of access to operate their systems. Specifically a problem arises if a communications component in the control network fails the ITS must be notified in order to investigate and correct the problem. The challenge is the ITS has not received any training on the CSRR as a SOS so they must rely on their basic network knowledge. The training provided to the ETR does not include any network systems which limits them to identifying which network component might have a problem. The conflict which frequently arises from this dichotomy is if the problem has several potential causes a great deal of back and forth exchange occurs in order to fully understand if the failure is truly a network problem or a communications component interfaced to the network. The lack of providing adequate training to both ratings creates a gap in their knowledge which creates a risk of a platform incurring a communications outage.

The solution to this would be to (1) designate the ETR personnel as member of the IAWF or (2) initiate a rating conversion of all ETR personnel to ITS which automatically places them in the IAWF, or (3) create a designation criteria of which systems require an IAWF certified technician and which ones can be maintained by other personnel. Within the submarine force this issue is not isolated to the ETR rating. Other ratings including combat systems and engineering ratings. On a macro level this problem is not isolated to the submarine force. The Navy as a whole faces challenges to determine how to fully train and equip their forces when many systems are now designed to interoperate so closely.

4. Production

The versions of CSRR prior to V3 were managed solely by SSC LANT. During this period the production team and installation teams worked closely together to build each CSRR prior to shipping to the installation site. The number of platforms in each class also helped since they were small enough to create a single design which could be

fielded in concert with the modernization periods. After assuming responsibility for the CSRR program and as lead systems integrator PMW770 developed and installed CSRR on the SSGNs replacing their legacy Trident IRRs using the VA CSRR design as a model. The SSBNs followed closely leveraging the work from the SSGN design while incorporating the components and systems necessary to support their strategic deterrence mission. The *Seawolf* class followed next leaving the LA class as the final exception. The production teams would build each ship set, perform a PITCO, configure it for the designated platform, an then pack and ship it.

The deployment of V3 coincided with the standup of the FRD and implementation of the global installation contract. Prior to V3 the production team would coordinate the delivery of all components and systems after performing a complete PITCO of the ship set. V3 proved to be a coordination challenge much more significant than earlier versions. First, the initial platform to receive V3 was the LA class, which also had the largest population of platforms and all of them required major modernization with a total replacement of their SCSS. Second, the number of new systems making up V3 each had their own mounting kits, software, alteration documentation, testing requirements and sparing approaches. The CSRR V3 production team had to contend with these issues as well as the differing bill of materials developed for each class. Third, some PORs insisted in delivering their systems directly to the installation site vice having it go through the PITCO process. This increased the risks of finding infant failures which delayed testing and drove up costs.

Several lessons were learned from the production process for V3. First, the production team manufactured all of the cables for the installation with at least one end completed in order to accelerate the installation. Second, the design drawings provided by the design agent were used to pre-assemble pieces into larger subassemblies again to accelerate the installation. A problem which arose from this approach is the AIT received the same drawings and would report materials missing which were actually consumed in the pre-fabrication process. Third, the production team developed the integrated SOVT merging all of the system verification testing into a larger, more comprehensive systems

verification. A result of this discovered the SPAWAR system for tracking installation completions does not have the capability of tracking the status of SOS installation and testing progress.

5. Installations and Synchronization of Installations into Block Upgrades

The establishment of the FRD significantly altered the existing installation process. Instead of each program office working directly with the IMO all functions were redirected to the FRD as the single point of contact for all installation issues. Additionally the FRD and IMO released a global installation contract which supported multiple award contracts and divided the installation responsibilities geographically with SSC LANT responsible for the east coast and SSC PAC responsible for the west coast. The standup of the FRD shifted the installation responsibilities away from the CSRR program production team. The shift significantly changed the relationship between the production and installation teams and eliminated the SSC LANT installation learning curve. The new installation contract discouraged development of a learning curve as new vendors with no prior CSRR experience were awarded the work. The lack of prior experience resulted in the CSRR production team altering their kitting approach as each new vendor wanted the installation kit created and delivered differently. Ultimately the FRD, IMO, and production team agreed on a standardized approach to how the kits would be produced, packed and shipped. However this did not address the issue of no effective learning curve for the AIT.

PEO C4I established a strategic goal for reducing the number of system variants installed afloat and ashore. To achieve this goal PEO C4I developed a synchronized fielding plan to align the fielding of systems to platform availabilities. This approach was an important first step but overlooked is the system development cycle. In the case of CSRR V3 several systems including ADNS, NMT, RFDACS and new workstations were consolidated into a single package. The recommended approach for a development cycle is working to an event based schedule. However, this approach conflicts with the calendar and budget based schedule. This is particularly acute when they have not been adjudicated to identify and mitigate schedule conflicts. The first installation of CSRR on

an LA was planned for early 2012. In order to meet the program schedule several significant design issues had to be resolved before SDVT and SAT could be accomplished. Solutions to these issues were identified prior to the installation but required procuring new materials and revising the installation drawings in order to allow prospective vendors to bid on the work. Daily meetings to track the status of material occurred between the program office, design agent and production agent. While this effort succeeded in obtaining the materials and getting them to the site a key consideration from a systems engineering and more importantly a SOS perspective is attempting to identify and resolve issues as early as possible. This may sound like common sense but a good heuristic is "Plan for the worst while praying for the best."

6. Cybersecurity

Information Assurance, or more recently known as Cybersecurity, has increased in importance as DOD's and the Navy's reliance on networks has grown. Prior to SCSS threats of cyber-attacks were practically unknown. Today cyber-attacks and scans for network vulnerabilities occur constantly. The importance of protecting the components in a network such as CSRR or SWFTS or SUBLAN is a clearly understood requirement. The challenge faced here is the often arbitrary approach to address cybersecurity. By arbitrary it does not mean policies and rules are being ignored. More accurately it means the application of cybersecurity architecture approach at the systems level often conflicts with the architecture approach needed for a SOS due to the interpretation of the standards. For example applying security technical implementation guides (STIG) to individual systems is an appropriate approach if it is meant to operate in an isolated or standalone manner. Getting authorization to waive or modify cybersecurity applications is often complicated and time consuming.

The transition from the defense information assurance certification and accreditation program (DIACAP) to the defense information assurance risk management framework (DIARMF) shown in Figure 31 represents an opportunity to design and implement more logical and effective approaches to IA and network defense. The DIARMF places more emphasis on managing the risk of a system getting penetrated vice

blindly following checklists which have little regard for the impact to the SOS. The approach a system follows using the DIARMF is the same approach the SOS IA engineer would follow.

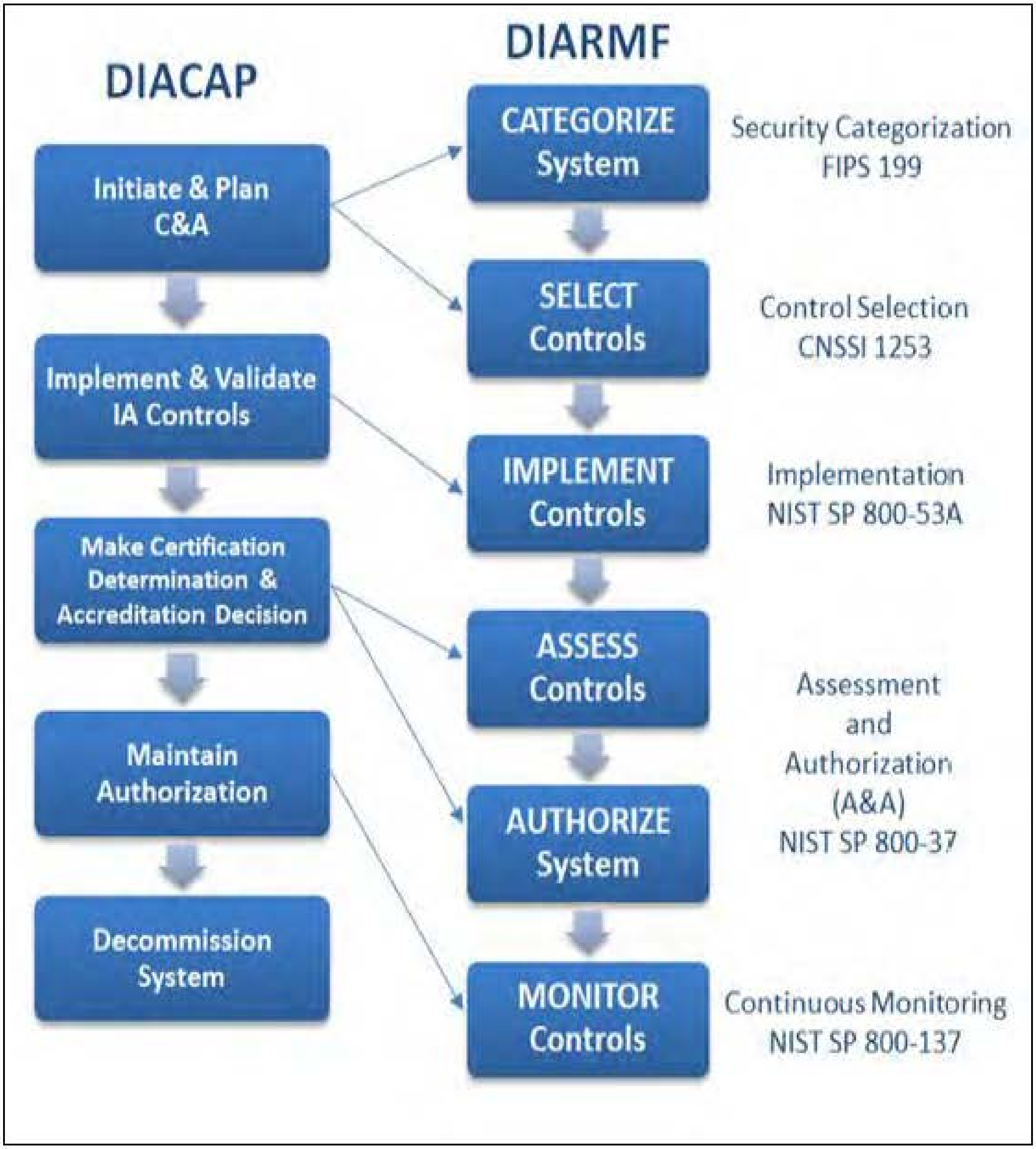

Figure 31. DIACAP to DIARMF Evolution (from Elamb 2013)

7. Sustainment

Sustainment of CSRR is challenging due to the heavy reliance on COTS by all of the POR systems including those components provided by the CSRR program. CSRR is not alone facing this challenge but the frequency of changes occurring to the other systems can have a unforeseen impact on the overall SOS if not assessed and possibly tested. The standard evolution of new technology is approximately 18 months. This is far faster than the typical defense acquisition program which might not have funding to begin design work for two years. Once funding is available it is unlikely a design will be completed in 18 months. Implementing the design in the current 24 month development period means at least one component that has reached end of life. Performing a six to eight year modernization cycle for all platforms means the systems have a large number of obsolete components within the first several installations.

SWFTS encountered this issue with their tech insertion / advanced processor build (TI/APB) approach. Similar to CSRR each TI/APB delivers an integrated suite of capabilities for the combat systems. A TI/APB is released every two years with the TI providing the hardware updates and the APB all software updates. Each TI/APB is planned to modernize a certain number of platforms before moving onto the next upgrade. The challenge is a change of a modernization schedules creates the risk of allowing a system to exceed its planned obsolescence and may have difficulties obtaining repair parts.

CSRR faced the same challenge when developing V3. The length of time between the initial design of the first platform in 2009 to completing the design of the last class in 2014 resulted in a number of obsolescence issues which in turn forced a number of design changes. The timing of the issue can impact the ability to sustain the systems out there while introducing new challenges. One solution may be to perform a lifetime buy to provide enough spares in inventory until a new solution is identified and deploys. Another is working the users to move the component from one platform to another to support the mission tasking. An approach to reduce obsolescence impacts may be

introducing smaller but more frequent changes vice over a longer period with larger changes. In either the case the SOS engineer must still assess the impacts these changes will have on the overall SOS architecture.

This problem is not unique to CSRR or any of the related systems. The challenge to the systems engineer is finding a suitable replacement. The challenge to SOS engineers is minimizing the impacts these changes induce in the overall SOS. The upgrading of a local software application on one system may degrade or disable remote operations located in another system. One recommendation to mitigate this is to provide loose coupling within the SOS but the extent to which loose coupling can be applied varies from system to system within the whole SOS (Director, Systems and Software Engineering 2008, 23).

I. RESEARCH QUESTIONS

At this point the following can be summarized from the research into the background of CSRR and system of systems engineering.

1. What is Common Submarine Radio Room and what Characteristics Classify it as a System of Systems?

Common Submarine Radio Room is an open architecture system of systems developed to support the submarine force communication requirements. This question determined if CSRR was a SOS justifying a case study analysis. If so, then what characteristics from the available literature regarding SOS would apply. The program documentation describes CSRR as a SOS but did not elaborate on specific characteristics. Vaneman (2013, 13) applies a "litmus test" to determine the applicability of a SOS. These consider if the individual systems "(1) Can operate independently from the SOS. (2) Have life-cycles that are individually managed. (3) Come together to achieve a capability that is unrealized by a single system alone" (Vaneman 2013, 13). Using this as a litmus test for CSRR the following is identified in answering the previous questions. Additional characteristics are listed in Table 19.

(1) Can the individual systems operate independently from the SOS? Each of the systems within CSRR is an individual POR which had to provide an operational view

identifying their role in the overall architecture. NMT is one example which has been installed on SCSS platforms and can operate independently of the CSRR SOS.

(2) Is the life cycle of each system individually managed? Each system such as ADNS, RFDACS and NMT within CSRR has their own life cycle management. Collective assessments are done with each version to determine the SOS impacts when changes are made.

(3) Do the systems come together to achieve a capability that is unrealized by the single system alone? Each individual is capable of providing a certain level of capability by itself. Prior to installing RFDACS antenna switching functions were performed using manual patch panels. Integrating RFDACs with the available radios and antennas provides automation and simultaneity capabilities that did not exist previously. NMT can be a standalone system but can provide asymmetric capabilities when paired with UHF and network systems.

Jamshidi (2009) identified the characteristics describing a SOS listed below in Figure 32 and Table 20. Resilience can be further classified examining the attributes of capacity, flexibility, tolerance, and cohesion which are supported by 14 principles (Jackson and Ferris 2012, 155). These characteristics were compared against CSRR to determine where it compared. The type of SOS is derived from the *System Engineers Guide for Systems of Systems* (Director, Systems and Software Engineering 2008). Governance is addressed using the information provided from the Naval Postgraduate School System of Systems Engineering and Integration course (Vaneman, 2013). These criteria were used to examine CSRR and determine if these characteristics can be used to describe it as a SOS.

Governance is addressed in more detail since this is of particular interest to many systems engineers and program managers. Governance is defined as “the organization, set of rules, policies, and decision-making criteria that will guide a System of Systems (SOS) to achieving its goals and objectives” (Vaneman 2013, 6). The characteristics listed in the center of Figure 32 and described in Table 21 define the two extremes of

defining a SOS. Governance of a SOS has four criteria defined in Table 21 which must be considered in order to determine if there is effective management.

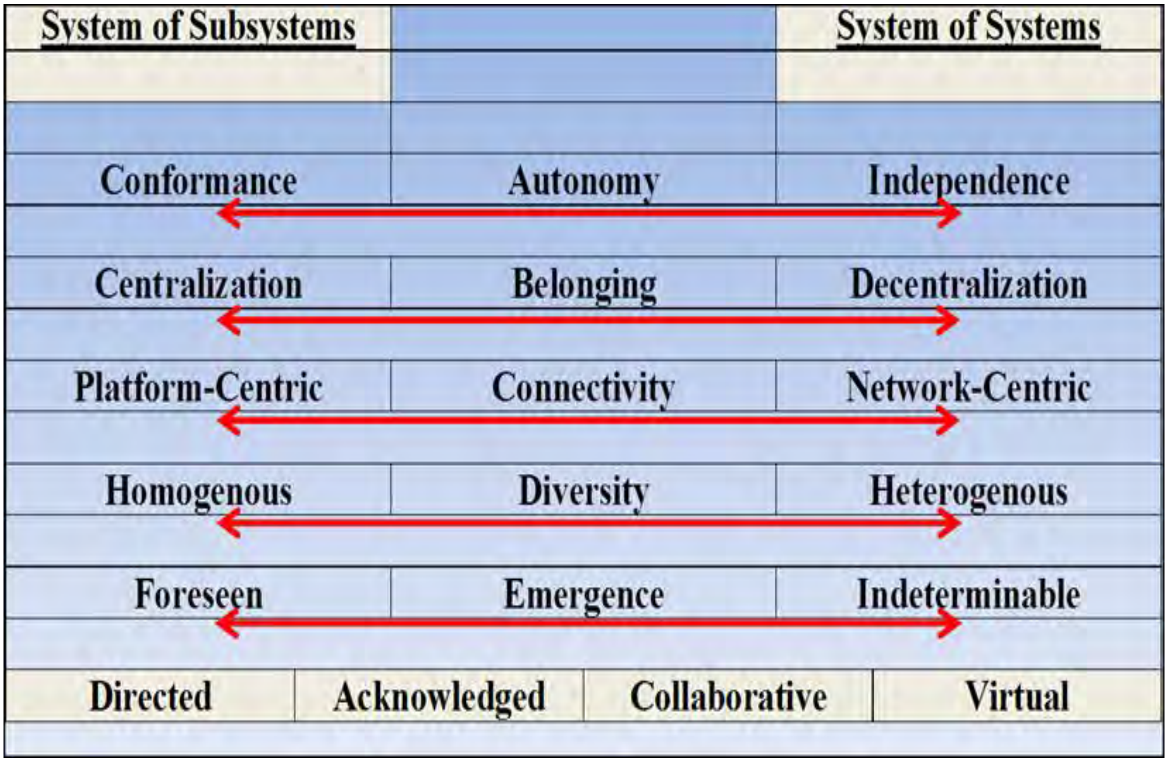

Figure 32. System of Systems Characteristics Spectrum (after Vaneman 2013, 20)

Table 20. System of Systems Characteristics and Applicability to Common Submarine Radio Room (after Jamshidi 2009)

SOS Characteristics	Description	Applicability to CSRR
Type of SOS (Director, Systems and Software Engineering, 2008)	Ad hoc, virtual, acknowledged and directed	CSRR is considered an acknowledged SOS since there is an assigned manager, funding and resources but must collaborate with other programs in order to deliver full capability
Evolutionary behavior (Jamshidi 2009, 193-194)	The evolution of a SOS can select or eliminate system configurations independently of the presence of other configurations" as long as the configurations are not subsequent system states	CSRR has demonstrated evolutionary characteristics as new technology is incorporated. Each change to add or remove a system has been assessed to determine its impact to the required capabilities
Self-Organization (Jamshidi 2009, 194)	Operational independence signifies that subsystems of an SOS are independent and useful in their own right. Managerial independence signifies that a system both is able to operate independently and actually is operating independently.	Operational independence is reflective of the systems comprising CSRR. They are independent from a funding and managerial perspective.
Heterogeneity (Jamshidi 2009, 194)	Heterogeneity is a strong driver of system complexity. A system is often heterogeneous on multiple layers simultaneously (e.g., size, architecture, life cycle, scientific area, and elementary dynamics)	CSRR can be considered heterogeneous since it is composed of a variety of systems to provide capability to the user
Emergence or Emergent Behavior (Jamshidi 2009, 85-86, 194; Vaneman 2013, 47)	The unexpected appearance of new properties in the course of development, evaluation, and operations Two types: weak and strong. Weak emergence can be foreseen through experience or modeling and simulation. Strong emergence is indeterminate	Weak emergence is addressed through the CSRR development approach and experiences from the deployment and sustainment
Redundancy (Jamshidi 2009, 199)	Traditional SOS are often designed with multiple redundant high-level subsystems; i.e., a functional requirement is satisfied by multiple	CSRR demonstrates Type I qualities through the use of multiple communications paths and networks

SOS Characteristics	Description	Applicability to CSRR
	design parameters. Type I have redundancy Type II has no redundancy.	
Autonomy (Jamshidi 2009, 48; Vaneman 2013, 47)	The ability to make independent choices or conform to a higher standard Two key aspects of system autonomy that must be preserved: technical autonomy and operational autonomy.	Each of the systems comprising CSRR have their own technical and programmatic requirements and can be considered autonomous.
Diversity (Jamshidi 2009, 49)	Diversity of needs and environmental diversity Can be Homogeneous or Heterogeneous	Each system in CSRR provides a capability but there is a large amount of commonality in the design
Complexity (Jamshidi 2009, 45)	The use of existing systems to create SOS solutions introduces unavoidable complexities, both in terms of constraints and consequences	CSRR has to deal with a number of technical, programmatic and funding constraints
Net Centricity or Connectivity (Director, Systems and Software Engineering 2008, 9; Vaneman 2013, 47)	Net centricity is relevant to all SOS within DOD Is the connectivity more platform centric or network centric	CSRR was designed to support net centric operations from the submarine platform
Belonging (Vaneman 2013, 47)	To be a member of a group or to have qualifications This can be centralized or decentralized	An acknowledge system can choose which systems to include or not. CSRR has a formal relationship with other PORs to deliver capability
Connectivity (Vaneman 2013,47)	Is connectivity more platform centric or network centric	CSRR is designed to support the submarine force but the principles could be applied to other platforms
Resilience (Jackson and Ferris 2012, 153)	The ability to adapt to changing conditions and prepare for, withstand, and rapidly recover from disruption	CSRR as a SOS incorporates a design capable of preparing for disruptions and if disrupted can recover within the required criteria
Governance	The organization, set of rules, policies	Governance is managed

SOS Characteristics	Description	Applicability to CSRR
(Vaneman and Jaskot 2013)	and decision making criteria that guide a SOS to achieve its goals and objectives	through program policy and guidance.

Table 21. Governance Criteria (from Vaneman 2013)

Criteria	Description	Application
Criteria 1: Organizational Structure, Standards and Policies	The organizational structure, standards, policies, and management environment must be understood to develop effective governance.	To be successful, governance must be consistent with the organization
Criteria 2: Governance Composition and Principles	Determines the degree of participation, responsiveness, consensus, inclusiveness, and accountability needed in the governance strategy	Virtual- SOS participants not included in the decisions of suggested changes. Directed- High degree of participation, inclusiveness, responsiveness, and consensus.
Criteria 3: Encapsulation	How transparent are the governance decisions, and how is enforcement managed within the SOS	Virtual- Most stakeholders do not care as long as they can achieve their missions and goals. Directed- Governance strategy is required to be more inclusive and transparent.
Criteria 4: Governance Effectiveness and Interoperability	Determines the effectiveness and interoperability attributes of the SOS	Virtual- Used for their own purposes. Should favor independence and decentralization. Difficult to predict or measure effectiveness. Directed- Designed to work together toward a common objective. Effectiveness and interoperability should focus on engineered effectiveness standards and tightly controlled interface standards.

Based on the characteristics, CSRR can be classified as an acknowledged SOS. An acknowledged SOS has recognized objectives, a designated manager, and resources assigned. The individual systems are managed separately in terms of ownership, funding, and sustainment. System changes are primarily managed by the parent program but are closely collaborated with the CSRR program. Many programs within DOD can be considered acknowledged SOS since they started out as a standalone or stovepipe system and over time were integrated to create or deliver capabilities needed by the user.

2. What are the Benefits and Challenges of Developing, Designing, Producing, Deploying, and Sustaining Common Submarine Radio Room as a System of Systems?

Prior to CSRR the typical approach to deliver a capability occurred in stovepipe fashion. Stovepipe systems provide all of the components within the overall program. The disadvantage of this approach is costs can be prohibitive, logistics can be very complex and prone to proprietary issues and performance may be limited to a very small set of requirements. For a submarine space and weight are critical considerations when determining what systems are needed. In the late 1990s the emphasis on COTS drove many programs to provide their own controller for their system, normally in the form of a laptop or desktop workstation. The space limitations in the submarine radio room immediately identified a need for establishing some means of centrally controlling all of the systems. The Trident IRR provided a central control capability but used a proprietary architecture. Additionally the following comment provides more insight into IRR

> IRR was actually the first real implementation of an integrated submarine communications system, although not really a SOS. While well-designed with excellent reliability, necessary modernization became cost prohibitive. In the days of shrinking budgets, dedicated interface protocols and bus-based systems have become unaffordable (Darlene Sullivan 2014, response to questionnaire)

As SCSS was deployed in response to the IMCS MNS, it served as the precursor for CSRR. The following quote captures some of the differences between SCSS and CSRR.

> SCSS was the first government integrated submarine communication system. The most significant architectural difference between SCSS and CSRR is the use of baseband switching. The miniaturization of crypto and the implementation of network interfaces obviated the need for baseband switching and removed throughput limitations. Additionally, the Integrated Network Manager (INM) in the SCSS controlled primarily the baseband switch (not the whole room), and changes to the baseband switch could be made easily, with updates to a database vs the INM software. However, these two technical differences both also have programmatic implications for modernization. The baseband switch allowed for a more well defined boundary and easier division of responsibility between PORs during the modernization phase. Additionally, software configuration updates for SCSS were mostly done with database changes; minimal software development was required. (Darlene Sullivan 2014 response to questionnaire)

The SCSS enabled the operator to be more effective but the multitude of individual controllers degraded their ability to maintain situational awareness of the communications status. Delivering individual systems also created problems for configuration management and ILS. Since systems were delivered individually the combination of different configuration increased exponentially. Just modernizing four systems could result in potentially 16 different configurations to track. Of the 42 LA submarines there were essentially 42 different configurations. The changes may have been minor, but the lack of accurate ILS documentation, training, and technical support made design changes and sustainment more challenging.

3. What Best Practices have been Identified and Implemented in the Common Submarine Radio Room Program and what Benefits have been realized in Terms of Cost, Performance, and Schedule?

The Department of Defense has implemented a number of initiatives to improve efficiency, contain costs and deliver capability. A major goal of these initiatives included identifying effective means of measuring program success and progress. The ability to measure progress using lagging indicators is relatively easy to do since elapsed time and performance criteria can be measured. The drawback of this approach is changes to a system or SOS must be made after the design is complete and this can be costly.

In 2003 the Navy began implementing continuous process improvement initiatives using Lean Six Sigma (LSS) to eliminate waste and identify opportunities using leading indicators to determine system and program performance. About 2006 PEO C4I initiated a number of process improvement events to reduce the total ownership costs of acquiring new capability.

In 2008 the Deputy Secretary of Defense directed all services and activities in DOD to begin using LSS. SSC LANT production and the CSRR ISEA began using LSS to find efficiencies and took an additional step to obtain capability maturity model integration (CMMI) level three certification from the Software Engineering Institute as well as meeting International Standards Organization (ISO) 9000/9001 standards.

Since 2008 the CSRR program completed six projects and SSC LANT another 15 related to increasing quality and reliability, reducing cycle time, improving development first pass yields and achieve costs savings and avoidance. The CSRR LSS events performed sponsored by the program office are listed in Table 22 with the objective and the outcome. Several of these were directed at specific systems but the overall results provided benefits to CSRR as a SOS. Investigation of RFDACS and BRR-6 identified gaps affecting capability, logistics, and requirements definition. Another confirmed planning and executing installation as a package of capabilities could deliver cost and schedule benefits. Implementing continuing process improvement demonstrates it is a practice which both a systems and system of systems should attempt to achieve. Effective process improvement also identifies leading indicators and benchmarks to assess performance of the SE activities and the overall program (Oppenheim, Murman and Secor 2009).

Table 22. Lean Six Sigma Projects Completed or in Progress

LSS Event	**Goal/Objective**	**Outcome/Comments**
CSRR Value Stream Analysis	Shorten the development cycle and identify the major activities	Identified all of the activities required to create a CSRR version. Established the development timeline at 24 months and identified $60M in cost avoidance for accelerating the LA version of CSRR
RFDACS Reliability Improvements	Identify the root cause of RFDACS failures and develop solutions	Isolated root causes of several problems. Developed groom procedures. Increased A_o to .97 and identified $10M cost avoidance for the fleet in reduced repairs
Testing Cycle Reduction	Eliminate duplicative testing performed during SDVT and SAT	Identified $128K in savings through eliminating duplicative testing
BRR-6 Reliability Improvements	Identify root cause of poor buoy performance and develop potential solutions	Identified 22 improvement recommendations for operating procedures, technical documentation, and operator and maintenance training. Developed a successful case to the CNO resource sponsor to fund improvements to the buoy
Installation Cost Sharing Productivity Improvement	Capture the costs of executing consolidated SOS installations	Validated consolidated installations are more effective. Identified $2.5M savings across the first five installations on LA platforms

4. What Lessons Learned Can be Applied to Future Versions of Common Submarine Radio Room and Common Radio Room for Surface Combatants?

Examination of the case studies, systems engineering, system of systems engineering and integration principles and acquisition policies identified where there have been successes and failures. Further understanding the history of how submarine communications has increased in complexity provided context in looking at how individual systems evolved into a SOS. These case studies were able to capture the lessons learned so they can be shared with others. Examining CSRR using the Friedman and Sage framework identified many of the learning principles noted in the case studies used in this research. Table 23 lists the learning principles identified from the information available regarding CSRR. The SOS principles identified would be applicable to other SOS regardless if they are a DOD or commercial entity.

One important observation noted is the fact too many opportunities are allowed to pass where a case study would be of value. The lessons learned, learning principles, or teachable moments could be captured and shared with others. LSS and CMMI events provide an opportunity for improvement as well using a systematic process to capture data and information while accomplishing a goal. Maier and Rechtin (2009) highlights a number of heuristics which are applicable to systems and systems of systems.

The learning principles identified in Table 23 from studying CSRR could be applied to any SOS. Several of these learning principles are related to one area and discussed in more detail below. These lessons can be shared with the current and future development of CSRR versions and are applicable to any system of systems. These lessons learned, or learning principles are listed below.

Table 23. CSRR Learning Principles

	Integration approach	The government acts as the integrator and program manager
A	**Requirements definition and management**	Clearly define the requirements and write the requirements clearly for the ENTIRE life cycle
B	**Systems architecture development**	Don't begin building before the architecture has been defined (or don't engineer just for the sake of engineering!)
C	**System/ subsystem design**	Design of an acknowledged system of systems must be shared to the maximum extent practicable.
D	**Systems integration and interfaces**	Maintain control of the system of systems at the interfaces from a physical, functional, and logical approach.
E	**Verification/ validation**	Design the test to test the design and trust but verify
F	**Deployment and post deployment**	Keep your customer(s) in mind
G	**Life cycle support**	Account for all of the "ilities" when developing the system of systems design
H	**Risk assessment and management**	Expect the unexpected and embrace change. It's inevitable
I	**System and program management**	A. Go fast whenever possible, otherwise go slow B. Perfect is the enemy of good enough C. Be a trusted partner and build effective relationships D. Most importantly create the most effective team possible and keep them engaged, motivated, and productive

1. Lesson One: Clearly Define the Requirements and Write the Requirements Clearly for the ENTIRE Life Cycle

While CSRR is a system of systems and has an approved set of requirements these must be balanced against the constituent subsystems to ensure the requirements of both are met. Many conflicts arise due to the conflicting requirements between program in different program offices. This is not limited to just within the individual program offices but also concerns the interactions of programs managed in different program

offices. Over 70 percent of a program's cost is in the operations and sustainment phase. This can be partially mitigated if the requirements are clear and do not conflict. Clear requirements with some clearly established flexibility to allow for evolving systems and capabilities should be considered. System of systems are evolutionary and have no defined ending date. However there are still three criteria that should be met when developing or evaluating requirements: (1) They must be precise, (2) they must be verifiable, and (3) they must be traceable (Madni and Sievers, 2014, 43). While this applies to systems level it is even more important for the SOS engineer since many times the requirements for an acknowledged system can be fuzzy and unclear. Reframing them in context of the criteria above will improve the probability of successfully building the right capability.

2. Lesson Two: Do Not Begin Building before the Architecture Has Been Defined (or Do Not Engineer Just for the Sake of Engineering!)

An open systems architecture must provide as much flexibility as possible to the constituent programs while maintaining the integrity of the whole system of systems. However it must also be clearly defined. This has been proven painfully true on more than one occasion. The F-111, TBMCS and International Space Station demonstrated attempting to build something without fully understanding the requirements and specifications invariably lead to building the wrong item or delivering the wrong capability. The lead SOS engineer must lead the team to define the SOS architecture as completely as possible in order to create and deliver the capabilities needed. This period involves a lot of creative thinking and almost no bending metal or turning screws. Clearly defining the architecture will improve the odds of building the right capability. The following quote from Maier and Rechtin (2009, 176) "A system will develop and evolve much more rapidly if there are stable intermediate forms than if there are not" often proves true when working with what is known to be factual vice what is undefined. This might sound like a direct SOS is the correct approach but this applies to acknowledged SOS as well.

3. Lesson Three: Design of an Acknowledged System of Systems must be Shared to the Maximum Extent Practicable

Common Submarine Radio Room displays many of the characteristics of an acknowledged system of systems. As a formal program CSRR engages with other programs to develop and deliver the set of capabilities needed by the submarine force. In order to be successful, open collaboration of information is paramount. Sharing information is a two-way activity. Constituent systems need information as well so they can attempt to meet the SOS requirements. Holding onto information and not sharing it undermines the integrity of the SOS and the ability to deliver the capability to the warfighter.

4. Lesson Four: Maintain Control of the System of Systems at the Interfaces from a Physical, Functional, and Logical Approach

One characteristic an acknowledged SOS must always consider is how much control should be exerted over the constituent systems and their interfaces. However, if there is no manager of the interfaces, then it is probably not an acknowledged SOS. A Direct SOS would have full and complete control over defining and directing what interface specifications must be followed. An acknowledged SOS does not control the other programs without agreements between the SOS and the constituent systems. CSRR attempts to maintain this relationship through constant engagement with the constituent programs. This includes working with new programs to ensure interoperability requirements are addressed, and determining the impact of changes to mature programs. If this is not possible, then it is incumbent for the SOS to assume this responsibility and share the information with the other programs.

One specific aspect that must be considered is when the interfaces between systems or within a system as it moves from one configuration to the next. The key piece is managing the interfaces so changes within the individual systems will not perturb the other systems. Maier and Rechtin pointed out in *The Art of Systems Architecting* (2009), "The greatest leverage in system architecting is at the interfaces. The greatest dangers are also at the interfaces."

5. Lesson Five: Go Fast Whenever Possible, Otherwise Go Slow

Common Submarine Radio Room as a system of systems requires effective and collaborative governance to manage delivery and sustainment of capability. This is not a parable related to the tortoise and the hare but more accurately the heuristic "haste makes waste." This normally occurs when event based and calendar based schedules conflict and artificial timelines are created. Few people like to admit they pad a schedule to allow for those moments when they cannot work on their project. Parkinsons law states "work expands so as to fill the time available for its completion" and the student syndrome is "2/3 of the work will be done in the last 1/3 of the time" (SPAWAR 2011; Goldratt 1997, 114–128). These relate to the first heuristic in there is always a normal tendency to address the crisis of the day and put off a task until it is close to or at a crisis stage. Then we make haste to get the project done in time to meet the deadline which is typically missed or the final product is incomplete. We see this occur almost everywhere we look. The problem is if the work is held off until the last moment the next heuristic from Murphy of "if anything can go wrong it will" kicks in. So the goal is to achieve as much progress as possible within the timeline that is allotted but do not expend energy to complete it too far in advance. When managing a SOS, there are many pieces which must be tracked. Maintaining a steady drumbeat with reasonable schedule expectations results in fewer crises and will keep the program development on track.

6. Lesson Six: Account for All of the "ilities" when Developing the System of Systems Design

Collaboration is key to ensuring the overall system of systems is supported for documentation, training and parts. When looking at the "ilities" (reliability, interoperability, maintainability, availability, usability) from an acknowledged SOS perspective the first issue that will be apparent is the different approaches each program followed to develop their system. The higher level intent was met but the result is different than another team. The primary focus for an SOS is interoperability. If the disparate systems cannot communicate with each other it's just a collection of

components. The other ilities must be balanced to ensure the optimization of one system does not occur at the sub-optimization of the others.

7. Lesson Seven: Design the Test to Test the Design, and Trust but Verify

Focus the testing on changes made to the system of systems. When building a system or system of systems a means to perform verification and validation has to occur. One of the lessons from the TBMCS is the requirements were unclear which in turn prevented effective test planning. When creating a test for an SOS verify the requirements themselves are clearly stated and testable via one or more means. When creating an acknowledged SOS, additional derived requirements will frequently be identified. These need to be included in the testing process and verified. In many cases the ability to fully test the SOS would require too much time and resources. These requirements need to be articulated as possible risks and a plan for testing them following employment of the SOS capabilities.

Common Submarine Radio Room has encountered this on several occasions when evaluating a system or component for integration into the SOS. The testing criteria were vaguely stated or established unrealistic conditions. One such example involved testing a system which required having four other platforms plus a shore station involved. The only problem is the system had not been fielded to the shore stations yet. This would be a valid SOS test but inappropriate for an individual system.

8. Lesson Eight: Expect the Unexpected and Embrace Change. It is Inevitable

Risks must be evaluated to determine if there is any potential for emergence. One of the SOS characteristics previously discussed was emergence. Emergence is really the unexpected occurring. If the changes to the SOS are well defined and documented the likelihood of emergence occurring should be low. Anticipating emergence may occur can provide the opportunity to identify alternate paths. CSRR has a relationship with a number of programs which are constantly modernizing their systems. Unless a close

relationship is maintained to keep abreast of their activities, the likelihood of emergence happening is high. Understanding there will always be change will minimize the amount of occasions to be surprised.

9. Lesson Nine: Perfect is the Enemy of Good Enough

This is one topic which causes much angst between acquisition and engineering teams. The acquisition team objective is to develop and procure a system which will meet the threshold requirements (a.k.a. the minimum standards). On the other hand, most engineering teams are driven to achieve the objective (a.k.a. possibly polishing a cannonball). Neither goal is wrong but all factors must be considered when designing and building a SOS. Unless it is a directed SOS, the lead engineer has no control over the individual systems requirements. If the POR is in development, opportunities exist to ensure the threshold and objective requirements are achievable.

Programs in development today are attempting to achieve perfection by establishing the threshold and objective to the same value. From a SOS perspective, this becomes unachievable since the overall performance is dependent on the individual systems performance. Establishing a more realistic set of requirements for the POR and the SOS also increase the probability of building a capability that is good enough. General Patton made the following statement which sums this up clearly "A good plan violently executed now is better than a perfect plan next week." (NDP 6 1995, 24)

10. Lesson Ten: Be a Trusted Partner and Build Effective Relationships

One of the most important characteristics of an effective lead systems or system of systems engineer is not the fact he can describe the technical specifications in detail. It is the ability to work with teams from the individual PORs in order to create consensus on a common goal. This is not a skill limited to systems engineering. The effective lead engineer will be able to understand the overall SOS goals and objectives and frame them from a system of systems perspective so all members of the teams can understand. Maier

and Rechtin (2009) stated, “If a system requires voluntary collaboration, the mechanism and incentives for that collaboration must be designed in.” From an SOS point of view this becomes critically relevant.

11. Lesson Eleven: Keep your Customer(s) in Mind

The system of systems must be able to collect performance data to determine what changes should occur to support the mission system of systems. A frequent problem seen in many SOS is the great deal of complexity built into the constituent systems. This may be okay if the planned operator is an engineer or a technician but presents potential problems when the operator is given a minimum amount of training. Whether it is a system or a SOS, it must be operable by an operator who has been given an appropriate level of training. For example, many of the CSRR technical manuals covered all of the systems within CSRR but did not cover the interfaces to the antennas. Conversely, the antenna technical manuals covered the antennas but did not cover the interfaces to CSRR, creating a gap where no documentation existed for the operator. When looking at the SOS from the user’s perspective, it is advantageous to have a CONOPS which describes how the SOS will be operated and maintained. Collecting SOS performance data from the users can be used to develop improvements and address deficiencies.

12. Lesson Twelve: Most Importantly Create the Most Effective Team Possible and Keep Them Engaged, Motivated and Productive

Regardless, if this is an engineering or management or academic issue, if there are no people on the team, nothing will get done. CSRR has had the advantage of recruiting and retaining a large number of talented engineers, technicians, testers, logistics and program management personnel. Creating synergy within the teams keeps them focused on the immediate problems while not ignoring the longer term issues and goals. The International Space Station case study pointed out maintaining a competent and experienced staff for over 20 years is a challenge. Getting the teams to get engaged and remain engaged can be a challenge especially when circumstances prevent scheduling face to face events. One issue noted during the development of CSRR V3 is the lack of

many of face to face meetings due to the federal budget challenges prevented a lot of interpersonal engagement which occurs when teams are together. When working with multiple systems the ability to engage and remain engaged is one of the key components to successfully managing a SOS program.

There is one last piece of this question which still needs to be answered in terms of the scope of this case study looking out beyond CSRR V3. The most recent acquisition program baseline (APB) (PMW770 2011a) extended the CSRR program out to FY 2030. Unlike a system which may have a defined modernization plan and requirements which are fairly static, a SOS is tied to the plans of the individual systems. A directed or collaborative SOS may require less negotiation due to their nature but acknowledged SOS will always be in a series of negotiations to assure changes within one program do not break a capability in another. Too often this is not identified until it is delivered to the end user. Common Submarine Radio Room has a large role in maintaining effective and open communications with other systems. Over time, this changes as people, policies and technology come and go. The version approach is planned to remain in place but will continue to evolve as well to meet the needs of the stakeholders. The Ohio SSBN replacement will deploy some version of CSRR, whether it is the one envisioned today remains to be seen. For the other domains considering using the CSRR model they have much to consider in order to define the architecture which supports their platforms and fits within the larger mission SOS role defined within the military strategic planning.

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V. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER INVESTIGATION

A. CONCLUSIONS

The C4I capabilities of the submarine force have evolved greatly over the last century. Expanding use of the RF spectrum and introduction of new technologies led to fielding systems of increasing complexity. As these systems were integrated into larger systems and systems of systems new capabilities emerged. The challenges experienced by DOD with the integration of these systems led to questions of ownership responsibilities of these new capabilities and how they should be managed. This in turn required defining a SOS and their characteristics. Depending on the type of SOS programmatic and systems engineering decisions are reached which may not be in the best interests of the SOS. Even today this is a major issue with many acknowledged SOS created within DOD having minimal oversight. Only recently has DOD recognized their acquisition approach must shift from an individual systems requirements mentality to a mission based mentality requiring a much more holistic examination of what is needed to achieve a given capability.

Systems engineering and SOS engineering share many characteristics but the applications differ by their approach. A system will have clearly defined requirements and a defined life cycle. SOS requirements are more generalized and possess an evolutionary life cycle which changes but does not end. A system normally has a single program manager whereas depending on the type of SOS may not have one at all. Most SOS within DOD are considered acknowledged SOS. Policy guidance from OSD is providing the framework for developing and managing systems of systems. Acquisition and systems commands have in turn recognized many of their products can be classified as a SOS or are a constituent component of a system of systems. This can be seen in Figure 33 by looking at a system such as ADNS supporting a C4I system of systems in CSRR which in turn supports the combat systems SOS in SWFTS to the Virginia platform system of systems which ultimately supports the larger mission system of systems.

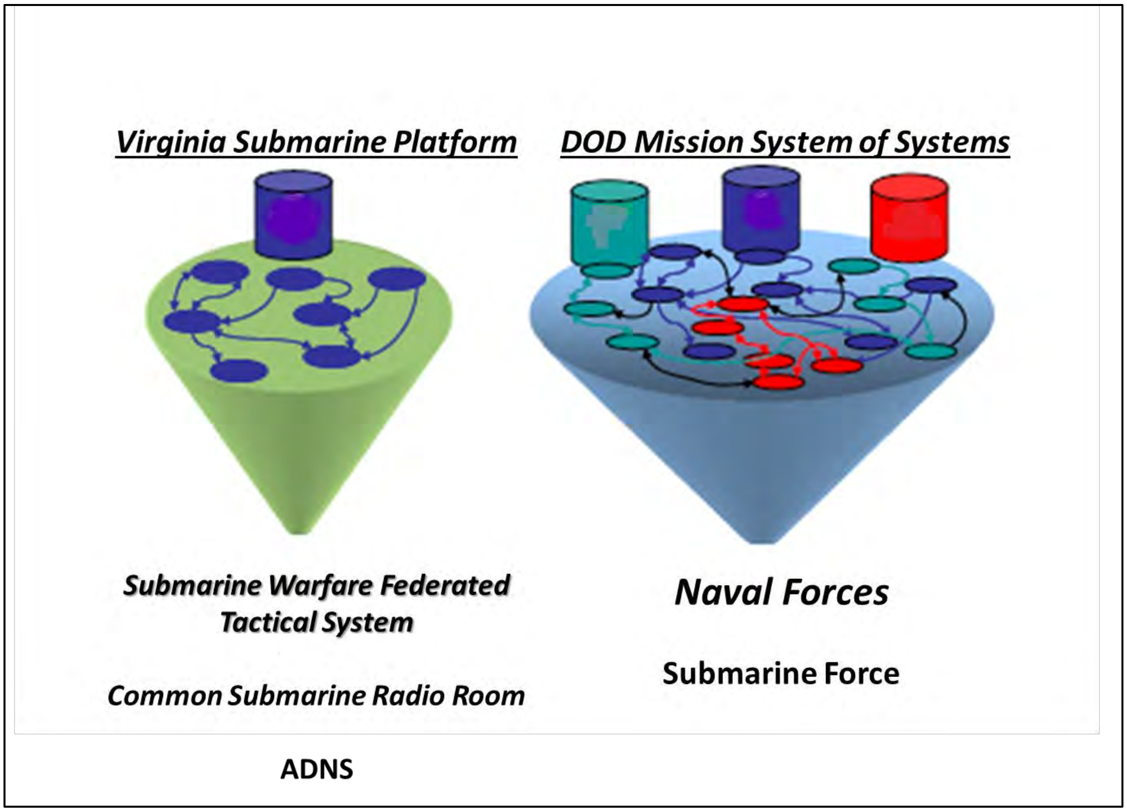

Figure 33. Systems to System of Systems Management Perspectives (after Director, Systems and Software Engineering 2008, 12)

The submarine force quickly recognized they needed to leverage the capability of these systems while bounding them with the limitations inherent for their platforms, specifically in terms of space, weight and power. The introduction of the Trident integrated radio room represented the first step toward employing a contractor furnished system of systems capability. The submarine communications support system took the next step by introducing automation and coordinated installation approaches. Common Submarine Radio Room is the culmination of these efforts while introducing open systems architecture designed to combine and leverage its constituent systems to deliver capabilities not possible in an individual manner. The approach for developing CSRR has evolved as well, moving from developing a specific increment version for each class to the point where a single version delivers a complete core capability capable of accounting for any unique platform characteristics. Clearly defining and balancing the requirements

of the constituent systems composing CSRR within the system of systems architecture means attempting to optimize one system over the others can be detrimental to the overall system of systems.

The development of case studies serves several purposes. Case studies provide opportunities to capture information about a particular event or system. The case studies may vary in their approach but the main result is identifying lessons learned or learning principles. NASA and the Air Force consider case studies to be a valuable means for capturing and sharing learning principles as explicit knowledge. The learning principles identified from the case studies confirmed CSRR would make a viable case study. The lack of available C4I case studies for other PEO C4I and SPAWAR systems reinforced the benefits of developing a case study involving systems managed within the CSRR program.

This research examined the question if CSRR met the characteristics to be classified as a system of systems. The SOS characteristics furthered defined CSRR as an acknowledged SOS. As an acknowledged SOS CSRR have requirements, funding and management. These must be balanced with the other systems that make up the whole SOS. System changes are primarily managed by the parent program but are closely collaborated with the CSRR program to avoid or minimize degradation or disruption of capability. As a system of systems, CSRR provides redundancy in several ways. If a communications path is not available another can be selected. If there is a network failure, alternate means to reroute or restore network management exist. Additionally, an examination of submarine communications demonstrated the evolutions from individual stove pipe systems to fully integrated and interoperable SOS can deliver more capability than if each system were employed separately. The research identified CSRR was not a result of a Manhattan project approach but rather another step in the evolution of submarine communications.

This case study confirmed systems engineering and system of systems engineering share similar qualities but are applied differently. The challenge lies in the SOS approach that is implemented. Most DOD SOS are considered acknowledged SOS due to each individual program maintaining its own program and funding responsibilities.

The net result is these systems create an iterative impact on other systems through introduction of new capabilities, phasing out old ones, changes to hardware or software, or changing operational planning. This increased emphasis on a SOS approach means a more holistic view is required when evaluating a new SOS or one that is already established. The guidance promulgated by Director, Systems and Software Engineering (2008) and the DASN (RDTE) 2013 draft provided a good starting point to begin implementing SOSE principles. Specifically the seven core elements a SOS engineer must be involved in encompass translating SOS capability objectives into SOS requirements to coordinating and monitoring changes to improve SOS performance (Director, Systems and Software Engineering 2008, 92). Another thought about the difference between systems engineering and SOS engineering is the level of complexity involved. A system can be decomposed into its discrete components. A radio can be decomposed to a power supply, amplifier, modulator and demodulator. A SOS considers the systems to be the discrete components. This changes the level of complexity the SOS engineer must consider when developing or changing a SOS.

In summary, the effective application of SOS engineering principles can be applicable to a variety of SOSs. The challenge will be related to the type of SOS and if there is a clear vision of what the SOS must be able to do. If designing a hospital the considerations need to include such factors as the location, type of hospital, services to be offered, etc. The same approach can be taken to build a command and control system. Or they can be applied to build an afloat communications architecture similar to CSRR. Case studies provide a means to capture these lessons learned from others so it can be retained as explicit knowledge and shared with future engineers, technicians and managers. In the end the SOS engineer must learn from the experience of others and be capable of balancing the needs of the systems and the SOS.

B. RECOMMENDED AREAS OF FURTHER STUDY

The body of knowledge regarding systems of systems is beginning to expand as recognition just how closely systems are tied together to provide new capabilities. This

case study examined how CSRR met the criteria for a system of systems and the lessons gained from the program. The following areas could possibly merit further investigation.

1. An examination to develop a case study of PEO SUBs approach to the development and sustainment of SWFTS would add to the knowledge base for the SOS community.
2. What resources exist to train SOS engineers? A study was performed for systems engineers so a similar study can emphasize the differences of a system and a SOS.
3. Investigate what leading indicators exist for measuring the performance of a SOS and how can they be utilized to provide a user insight to potential degradations.
4. An examination of the SOS approach to the DOD cloud development projects
5. An assessment of implementing a quality function deployment approach to evaluate the benefits or risks of making changes to a SOS.

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LIST OF REFERENCES

Adcock, Rick. ed. 2014. "Case Studies." *BKCASE Editorial Board. The Guide to the Systems Engineering Body of Knowledge* (SEBoK) v. 1.3. Hoboken, NJ: The Trustees of the Stevens Institute of Technology. Accessed July 12, 2014. http://www.sebokwiki.org/w/index.php?title=Case_Studies&oldid=49757

American Radio Relay League. 2009. "Remembering 'Nautilus 90 North' Replica of USS Nautilus Radio room." Accessed March 21, 2014. http://www.arrl.org/news/remembering-ldquo-nautilus-90-north-rdquo

Anderson, Edward. 2014. "Submarine Inboard Systems- Program Overview for PMW770 DPM." San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence, Undersea Integration Program Office.

Assistant Secretary of the Navy for Research, Development and Acquisition. 2005. *Memorandum for Program Executive Officer, Command, Control, Communications, Computers, Intelligence and Space Subject: Acquisition Category Designation Change Request for Common Submarine Radio Room*. Washington DC: Assistant Secretary of the Navy for Research, Development and Acquisition.

———. 2006. *Naval "System of Systems" Systems Engineering Guidebook Version 2.0*. Washington, DC: Assistant Secretary of the Navy for Research, Development, and Acquisition.

Bahill, Terry and William Chapman. 1994. "Understanding Systems Engineering through Case Studies." *Systems Engineering. The Journal of the National Council on Systems Engineering* 1: 145–154. Accessed August 08, 2014. http://www.sie.arizona.edu/sysengr/publishedPapers/CaseStudies.pdf

Bertalanffy, L. von. 1968. *General System Theory: Foundations, Development, Applications*, rev. ed. New York: Braziller.

Berteau, David, Guy Ben-Ari, Joshua Archer, and Sneha Raghavan. 2013. "Identifying Governance Best Practices in Systems-of-Systems Acquisition." In *Proceedings of the Tenth Annual Acquisition Research Symposium*. Monterey, CA: Naval Postgraduate School.

Brooks, Roland T., and Andrew P. Sage. 2006. "System of Systems Integration and Test." *Information Knowledge Systems Management* 5(4): 261–280. Accessed July 22, 2014. EBSCOhost

Buede, Dennis. 2000. *The Engineering Design of Systems: Models and Methods.* New York, NY: John Wiley and Sons, Inc.

Burroughs, Jerry. 2012. *2013-2018 PEO C4I Strategic Plan Version 0, September 2012.* San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence. Accessed December 19, 2012. http://www.public.navy.mil/spawar/PEOC4I/Documents/PEO%20C4I%20Strategic%20Plan%20-%20FY13%20-%20FINAL.pdf

Carter, Ashton. 2013. *Operation of the Defense Acquisition System*. Interim Department of Defense Instruction 5000.02. Washington DC: Deputy Secretary of Defense. Accessed July 23, 2014. http://www.dtic.mil/whs/directives/corres/pdf/500002_interim.pdf

Chief of Naval Operations. 1995. *Naval Doctrine Publication 6 Naval Command and Control.* Washington, DC.

Chief of Naval Operations N2N6. 2012. *Navy Training Systems Plan for the Common Submarine Radio Room.* Washington, DC: Chief of Naval Operations N2N6

Chief of Naval Operations N8. 1998. OPNAV N810. *Capstone Requirements Document For Submarine Exterior Communications System*. Washington, DC: Deputy Chief of Naval Operations Integration of Capabilities and Resources.

———. 2003. OPNAV N8. *Capstone Requirements Document for Submarine Exterior Communications System* revision 1. Washington, DC: Deputy Chief of Naval Operations Integration of Capabilities and Resources.

Chief of Naval Operations N61 and N87. 1998. *Submarine Communications Master Plan*. Washington, DC: Chief of Naval Operations N61 and N87.

Chief of Naval Operations N81. 1995. *Integrated Maritime Communications System Mission Needs Statement* (Serial M063-06-95). Washington DC: Chief of Naval Operations N81.

Chief of Naval Operations N87. 1995. *FY96 Submarine Communications Master Plan*. Washington DC: Chief of Naval Operations Submarine Warfare Directorate. Accessed July 23, 2014. http://fas.org/man/DOD-101/navy/docs/scmp/

Chislaghi, Don, Richard Dyer and Jay Free. 2010. *KC-135 Simulator Systems Engineering Case Study*. Wright Patterson, OH: Air Force Center for Systems Engineering, Air Force Institute of Technology. Accessed August 02, 2014. www.dtic.mil/dtic/tr/fulltext/u2/a538401.pdf

Clay, Thomas. 2008. “World War II United States Naval Submarine Operations against the Empire of Japan.” Accessed April 21, 2014. http://wwii-submarine-operations.tripod.com/technology.htm#_ftnref46

Collens, Josiah and Bob Krause. 2005. *Theater Battle Management Core System.* Wright Patterson, OH: Air Force Center for Systems Engineering, Air Force Institute of Technology. Accessed June 20, 2014. https://acc.dau.mil/adl/en-US/37601/file/9106/Theater%20Battle%20Management%20Core%20System%20SE%20Case%20Study%20-%20Collens%20_%20Krause.pdf

Conner, John, James Caldwell, and Barry Bruner. 2012. *Design for Undersea Warfare*, rev 1. Norfolk, VA; Pearl Harbor, Hi, Washington, DC: Commander Submarine Forces, Commander Submarine Forces, Pacific Fleet, Chief of Naval Operations, Director of Undersea Warfare N97.

Dahmann, Judith. 2009. "Systems Engineering for Department of Defense Systems of Systems." *System of Systems Engineering—Innovations for the 21st Century*, edited by Mohammed Jamshidi, 218–231. New York John Wiley & Sons.

Dahmann, Judith, George Rebovich and Jo Ann Lane. 2008. "Systems Engineering for Capabilities." *Crosstalk the Journal of Defense Software Engineering*. Accessed July 27, 2014. http://www.crosstalkonline.org/storage/issue-archives/2008/200811/200811-Dahmann.pdf

Dahmann, Judith, George Rebovich, Jo Anne Lane and Ralph Lowry. 2010. "Systems of Systems Test and Evaluation Challenges." Accessed July 12, 2014. http://www.acq.osd.mil/se/docs/Dahmann-IEEE-SoSE%202010.pdf

———. 2011. *An Implementers' View of Systems Engineering for Systems of Systems*. Montreal, Canada: Presentation at the 2011 IEEE International Systems Conference. Accessed February 10, 2014. http://www.acq.osd.mil/se/docs/ImplementerViewSE-SOS-Final.pdf

Defense Acquisition University. 2008. *Defense Acquisition Guidebook*. Ft Belvoir, VA: Defense Acquisition University. https://dag.dau.mil/Pages/Default.aspx

Defense Systems Management College. 2001. *Systems Engineering Fundamentals.* Ft Belvoir, VA: Defense Systems Management College Defense Acquisition University Press.

Department of Defense Inspector General. 2005. *Acquisition, Audit of the Common Submarine Radio Room* (D-2006-001). Washington, DC: Department of Defense Inspector General. Accessed August 17, 2014. http://www.DODig.mil/audit/reports/FY06/06-001.pdf

Deputy Assistant Secretary of the Navy for Research, Development, Test and Evaluation. 2013. *Naval "System of Systems" Systems Engineering Guidebook Version 3.x.* Washington, DC: Deputy Assistant Secretary of the Navy for Research, Development, Test and Evaluation.

Department of Defense. 2013. *Interim DOD Instruction 5000.02, Operation of the Defense Acquisition System.* Washington, DC: Undersecretary of Defense for Acquisition, Technology and Logistics.

Derencin, Robert. 2002. "Radio Communications of German U-boats in WWI and WWII." Accessed April 10, 2014. http://uboat.net/articles/index.html?article=35

Director, Operational Test and Evaluation (DOT&E). 2000. *DOT&E FY00 Annual Report Submarine Exterior Communications System (SUBECS)*. Washington, DC: Director Operational Testing and Evaluation. Accessed March 21, 2014. http://www.dote.osd.mil/pub/reports/FY2000/

Director, Systems and Software Engineering. 2006. *System of Systems Engineering Guide: Considerations for Systems Engineering in a System of Systems. For System of Systems Pilot Project* Version .9. Washington DC: Deputy Under Secretary of Defense (Acquisition and Technology), Office of the Under Secretary of Defense (Acquisition, Technology and Logistics). Accessed July 27, 2014. https://www.dsiac.org/sites/default/files/SOS-SE-Guide.pdf

———. 2008. *Systems Engineering Guide for Systems of Systems Version 1.0.* Washington, DC: Office of the Deputy Under Secretary of Defense Acquisition, Technology and Logistics (AT&L). Accessed July 27, 2014. http://www.acq.osd.mil/se/docs/SE-Guide-for-SoS.pdf

Elamb, Rob. 2013. "DIARMF Process." Accessed August 12, 2014. http://diarmfs.com/diarmf-process/

Friedman, George and Andrew Sage. 2003. "Case Studies of Systems Engineering and Management in Systems Acquisition." *System Engineering* 7(1): 84–96. Accessed July 13, 2014. http://onlinelibrary.wiley.com.libproxy.nps.edu/doi/10.1002/sys.10057/pdf

Gansler, Jacques, William Lucyshyn and John Rigilano. 2012. "Implementing System-of-Systems Governance" [document A568387] College Park, MD: University of Maryland, Center for Public Policy and Private Enterprise- School of Public Policy. Accessed June 20, 2014. http://www.dtic.mil.

General Dynamics. 2008. "Automated Digital Network System (ADNS)" datasheet. Taunton, MA: General Dynamics C4 Systems. Accessed April 25, 2014. http://www.gdc4s.com/Documents/Top%20Level%20Areas/Markets/US%20Department%20of%20Defense/Navy/ADNS_datasheet1.pdf

———. 2014. "Digital Modular Radio (DMR)." General Dynamics C4 Systems. Accessed August 12, 2014. http://www.gdc4s.com/dmr

Goldratt, Eliyahu. 1997. *Critical Chain a Business Novel.* Great Barrington, MA: North River Press Publishing Corporation.

Government Accountability Office. 2013. *Report to Congressional Committees High-Risk Series: An Update*. Washington DC: United States Government Accountability Office. Accessed July 14, 2014. http://www.gao.gov/assets/660/652133.pdf

Grenville, Delia, Brian Kleiner, and John Newcomb. 2004. *Miniature Seeker Technology Integration, Optimizing the Whole System.* Blacksburg, VA: Virginia Polytechnic Institute. Accessed April 04, 2014. http://www.nasa.gov/pdf/293212main_58529main_msti_casestudy_042604.pdf

Griffin, John. 2004. *C-5A Galaxy Systems Engineering Case Study*. Wright Patterson, OH: Air Force Center for Systems Engineering, Air Force Institute of Technology. Accessed August 02, 2014. https://acc.dau.mil/adl/en-US/37598/file/9103/C-5A%20Galaxy%20SE%20Case%20Study.pdf

Griffin, John and James Kinnu. 2007. *B-2 Systems Engineering Case Study.* Wright Patterson, OH: Air Force Center for Systems Engineering, Air Force Institute of Technology. Accessed March 28, 2014. www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA464771

Harris, Brayton. 2010. "World Submarine History Timeline Part Four: 1941–2000." 06 February. Accessed August 01, 2014. http://www.submarine-history.com/NOVAfour.htm

Hendricks, Eric and LorRaine Duffy. 2012. "Undersea Connectivity Roadmap (UCR)." Report to PMW770. San Diego, CA: Space and Naval Warfare Systems Center Pacific.

Howeth, Linwood. 1963. *History of Communications-Electronics in the United States Navy. Bureau of Ships and Office of Naval History*. Washington, DC: United States Government Printing Office, 1963. Library of Congress Catalogue Number: 64-62870. Accessed April 11, 2014. http://earlyradiohistory.us/1963hw.htm

Hummel, John. n.d. "USS Torsk (SS-423) radio room." NavSource Online: Submarine Photo Archive. Accessed March 21, 2014. http://www.navsource.org/archives/08/0842322.jpg

Haskins, Cecilia ed. 2012. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, version 3.2.2.* San Diego, CA: International Council on Systems Engineering, INCOSE-TP-2003-002-03.2.2. Accessed April 08, 2013. http://www.sebokwiki.org/wiki/INCOSE_Systems_Engineering_Handbook

Jackson, Scott and Timothy Ferris. 2013. "Resilience Principles for Engineered Systems." *Systems Engineering* 16(2). Accessed November 21, 2013. http://onlinelibrary.wiley.com.libproxy.nps.edu/doi/10.1002/sys.21228/pdf

Jacques, David and Dennis Strouble. 2010. *A-10 Thunderbolt II (Warthog) Systems Engineering Case Study.* Wright Patterson, OH: Air Force Center for Systems Engineering, Air Force Institute of Technology. Accessed August 02, 2014. http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA530838

Jamshidi, Mohammad, ed. 2009. *System of Systems Engineering: Innovations for the 21st Century.* Hoboken, NJ: Wiley.

Johnson, Mark. 2009. "System-of-systems standards." *System of Systems Engineering: Innovations for the 21st Century*, edited by Jamshidi, Mohammad, 451–462. Hoboken, NJ: Wiley

Joint Chiefs of Staff. 2011. *Joint Operations Planning.* Washington, DC: Joint Chiefs of Staff. Accessed August 17, 2014. http://www.dtic.mil/doctrine/new_pubs/jp5_0.pdf

———. 2012. *Joint Capabilities Integration and Development System (JCIDS) Manual*. Washington, DC: Defense Acquisition University. Accessed August 17, 2014. https://acc.dau.mil/adl/en-US/267116/file/41245/JCIDS%20Manual%20-%2019%20Jan%202012.pdf

Keller, John, ed. 2012. "Navy asks industry to upgrade integrated submarine communications system software." *Military and Aerospace Electronics*. December 9. Accessed July 23, 2014. http://www.militaryaerospace.com/articles/2012/12/submarine-radio-room.html

King, Mak and Michael Ricchio. 2010, spring. "Military Satellite Communications: Then and Now." *Crosslink Magazine*. Accessed July 13, 2014. http://www.aerospace.org/2013/12/12/military-satellite-communications-then-and-now/

Kinzig, Bill. 2010. *Global Hawk Systems Engineering Case Study*. Wright Patterson, OH: Air Force Center for Systems Engineering, Air Force Institute of Technology. Accessed April 04, 2014. www.dtic.mil/dtic/tr/fulltext/u2/a538761.pdf

Longacre, Jacob, Gerald Exley, and Craig McMillan. 1998. "Voices from the Deep the New Age of Submarine Communications." Accessed May 23, 2014. http://www.navy.mil/navydata/cno/n87/usw/autumn98/voices.htm

Madny, Azad and Michael Sievers. 2014. "Systems Integration: Key Perspectives, Experiences, and Challenges." *Systems Engineering* 17 (1): 37–51

Maier, Mark and Eberhardt Rechtin. *The Art of Systems Architecting*. Boca Raton, FL: CRC Press.

Manthorpe, Will. 1996. “The Emerging Joint System of Systems: A Systems Engineering Challenge and Opportunity for APL.” *John Hopkins APL Technical Digest* 17 (3): 305–310

Mattice, James. 2003. *Hubble Space Telescope Systems Engineering Case Study.* Wright Patterson, OH: Air Force Center for Systems Engineering, Air Force Institute of Technology. Accessed August 02, 2014. https://acc.dau.mil/adl/en-US/37600/file/9105/Hubble%20Space%20Telescope%20SE%20Case%20Study%20-%20JJ%20Mattice.pdf

MITRE Corporation. 2014. *Systems Engineering Guide.* Bedford, MA: Accessed July 10, 2014. http://www.mitre.org/sites/default/files/publications/se-guide-book-interactive.pdf

Morris, Ed, Pat Place, and Dennis Smith. 2006. *System-of-Systems Governance: New Patterns of Thought* [CMU/SEI-2006-TN-036]. Hanscom AFB, MA: Software Engineering Institute. Accessed May 16, 2014. http://resources.sei.cmu.edu/asset_files/TechnicalNote/2006_004_001_14738.pdf

National Aeronautics and Space Administration. 2007. *Systems Engineering Handbook* (NASA/SP-2007-6105) Rev1. Hanover, MD: National Aeronautics and Space Administration Center for Aerospace Information. Accessed April 10, 2014. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080008301.pdf

———. 2009. “Syncom, the First Geosynchronous Satellite - GPN-2002-000123.jpg.” Accessed May 08, 2014. http://dayton.hq.nasa.gov/IMAGES/LARGE/GPN-2002-000123.jpg

———. 2011. *Case Study Methodology (NASA GSFC-Methodology-1Rev. 01/19/ 11).* Greenbelt, MD: National Aeronautics and Space Administration Goddard Space Flight Center. Accessed April 4, 2014. http://www.nasa.gov/centers/goddard/pdf/292342main_GSFC-Methodology-1.pdf

Naval Network Warfare Command. 2008. *Naval Telecommunications Publication (NTP) 4E Naval Communications.* Norfolk, VA: Naval Network Warfare Command. Accessed April 21, 2014. http://info.publicintelligence.net/USNavy-NTP4E.pdf

Naval Undersea Warfare Center. 2008. *Common Submarine Radio Room SSBN Variant Increment 1 Version 1 (1.1.3.0) System/Subsystem Design Description (SSDD),* Document Number: 341-08-007-5. Newport, RI: Naval Undersea Warfare Center Division Newport.

———. 2011. *Common Submarine Radio Room Los Angeles Variant Increment 1 Version 3 (1.3.4.0) System/Subsystem Design Description (SSDD) (Pre-SDVT Completion/Pre-Problem Report Resolution Version)* Document Number: 341-11-028-5. Newport, RI: Naval Undersea Warfare Center Newport Division Newport.

———. 2012a. *Common Submarine Radio Room Virginia Variant Increment 1 Version 3 (1.3.0.0) System/Subsystem Design Description (SSDD)* Document Number: 341-12-002-5. Newport, RI: Naval Undersea Warfare Center Division Newport.

———. 2012b. *Common Submarine Radio Room Virginia Variant Increment 1 Version 3 System Design Verification Test Report*. Test Report Number 341-10-029-3B. Newport, RI: Naval Undersea Warfare Center Division Newport.

———. 2014. *PEO C4I PMW770 Submarine Communications Program Review*. Newport, RI: Naval Undersea Warfare Center Division Newport.

O'Brien, Patrick and John Griffin. 2007. *Global Positioning System Systems Engineering Case Study*. Wright-Patterson Air Force Base, OH: Air Force Center for Systems Engineering Air Force Institute of Technology. Accessed April 04, 2014. http://www.afit.edu/cse/casedocs/files/GPS%20SE%20Study%20Final%20Report%20_4%20Oct%2007.pdf

Office of Secretary of Defense. 2012. *Selected Acquisition Report Navy Multiband Terminal Satellite (NMT).*Washington DC: Office of Secretary of Defense. Accessed April 30, 2014. http://www.DOD.mil/pubs/foi/logistics_material_readiness/acq_bud_fin/SARs/2012-sars/13-F- 0884_SARs_as_of_Dec_2012/Navy/NMT_December_ 2012_SAR.pdf

Oppenheim, Bohdan, Earl Murman and Deborah A. Secor. 2011. "Lean Enablers for Systems Engineering." *Systems Engineering* 14(1): 29–55. Accessed August 10, 2014. http://onlinelibrary.wiley.com.libproxy.nps.edu/doi/10.1002/sys.20161/pdf

Patterson, C., Rachel Dubin and Karen J. Richter. 2004. *Activities Related to Systems Engineering.* Alexandria, VA: Institute for Defense Analysis. Accessed November 24, 2013. http://www.dtic.mil/dtic/tr/fulltext/u2/a437444.pdf

Program Executive Office C4I. 2006. *Concept of Operations for Modernization Management of PEO C4I.* San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence.

———. 2012. "Products and Services." Accessed April 18, 2014. http://www.public.navy.mil/spawar/PEOC4I/ProductsServices/Pages/default.aspx

———. 2014. "CANES—Consolidated Afloat Networks and Enterprise Services." Accessed August 18, 2014. http://www.public.navy.mil/spawar/PEOC4I/ProductsServices/Pages/CANES.aspx

Program Management Warfare 173. 2002. *Common Submarine Radio Room Acquisition Strategy.* San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence. Submarine Communications Program Office.

Program Management Warfare 770 Submarine Integration Program Office. 2006. *CSRR Capability Production Document (KM/DS Control Number 06-52758035-00).* San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence. Submarine Integration Program Office.

———. 2007. *Systems Engineering Plan of the Common Submarine Radio Room Version 1.2 Full Rate Production Decision.* San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence, Submarine Integration Program Office.

———. 2008a. *Common Submarine Radio Room Acquisition Plan/Acquisition Strategy (AP/AS) for Gate 6 Sufficiency Review [AP#7-005(Revision 1)].* San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence, Submarine Integration Program Office.

———. 2008b. *Common Submarine Radio Room (CSRR) Integrated Logistics Support Plan (ILSP).* San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence Submarine Integration Program Office.

———. 2011a. *Common Submarine Radio Room Acquisition Program Baseline Change 2*. San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence Undersea Integration Program Office.

———. 2011b. *Operations Guidance for Common Submarine Radio Room (CSRR) Increment 1 Version 3 (Version 1.0) (Draft).* San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence Undersea Integration Program Office.

———. 2012a. *Test and Evaluation Master Plan (TEMP) Revision 5 for the Common Submarine Radio Room (CSRR) Test and Evaluation Identification Number (TEIN) 1647*. San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence Undersea Integration Program Office.

———. 2012b. "SWFTS TI-12/APB-11 NPES Frog Charts (Planned end state) DRAFT." San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence Undersea Integration Program Office.

———. 2013a. *Common Submarine Radio Room SSGN Variant Increment 1 Version 3 System Design Verification Test Report*. San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence Undersea Integration Program Office.

———. 2013b. *Common Submarine Radio Room SSBN Variant Increment 1 Version 3 System Design Verification Report.* San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence Undersea Integration Program Office.

———. 2014. *Common Circuit Matrix for all Common Submarine Radio Room Variants and Submarine Communications Support System*. San Diego, California: Program Executive Officer for Command, Control, Communications, Computers and Intelligence Undersea Integration Program Office.

Pyster, Arthur and David Olwell, eds. 2013. *The Guide to the Systems Engineering Body of Knowledge (SEBoK)* v. 1.2. Hoboken, NJ: The Trustees of the Stevens Institute of Technology. Accessed July 12, 2014. www.sebokwiki.org.

Richardson, John, James Caldwell, and Richard Breckenridge. 2012. *Design for Undersea Warfare*. Norfolk, VA: Commander Submarine Forces. Accessed July 23, 2014. http://www.public.navy.mil/subfor/hq/PDF/Undersea%20Warfare.pdf

Richey, G. Keith. 2005. *F-111 Systems Engineering Case Study*. Wright-Patterson AFB, OH: Center for Systems Engineering at the Air Force Institute of Technology. Accessed July 23, 2014. https://acc.dau.mil/CommunityBrowser.aspx?id=37599

Ross, John. 2013. *Common Submarine Radio Room Requirements, Design, Integration and Test Process Book* (Version 1.0). San Diego, CA: Program Executive Officer for Command, Control, Communications, Computers and Intelligence, Undersea Integration Program Office.

Sage, Andrew and Christopher D. Cuppan. 2001. "On the Systems Engineering and Management of Systems of Systems and Federations of Systems." *Information Knowledge Systems Management* 2(4): 325–345. IOS Press. Accessed July 22, 2014. http://web.a.ebscohost.com.libproxy.nps.edu

Soy, Sue. 1997. "The Case Study as a Research Method." Austin, TX: Unpublished paper. Accessed August 08, 2014. https://www.ischool.utexas.edu/~ssoy/usesusers/l391d1b.htm

Space and Naval Warfare Systems Center Atlantic. 2014. "Undersea Integration Program Office PMW770 Program Management Review FY14 Mid-Year Review. 27–28 March." Charleston, SC: SPAWAR Systems Center Atlantic.

Space and Naval Warfare Systems Command. 2011. *Module 40 Critical Chain Project Management.* San Diego, CA: Space and Naval Warfare Systems Command Lean Six Sigma Continuous Process Improvement Office.

———. 2012. "System of Systems Engineering (SoSE) Policy, Guidance, and Goals." San Diego, CA: Space and Naval Warfare Systems Command Chief Engineers Office.

———. 2014a. *System of Systems Engineering (SOSE) Resources & Tools* brief to incoming SPAWAR Commander. San Diego, CA: Space and Naval Warfare Systems Command Chief Engineers Office.

———. 2014b. "IDEA Requirements Tree." San Diego, CA: Space and Naval Warfare Systems Command Chief Engineers Office.

Stjelja, Mirela. 2013. "The Case Study Approach: Some Theoretical, Methodological and Applied Considerations." Edinburgh, Australia: Land Operations Division DSTO Defence Science and Technology Organisation. Accessed June 20, 2014. www.dtic.mil/get-tr-doc/pdf?AD=ADA588465

Stockman, Bill, Joe Boyle, and John Bacon. 2010. "International Space Station Systems Engineering Case Study." Wright Patterson, OH: Air Force Center for Systems Engineering, Air Force Institute of Technology. Accessed July 23, 2014. http://spacese.spacegrant.org/uploads/images/ISS/ISS%20SE%20Case%20Study.pdf

Vaneman, Warren and Richard Budka. 2013. "Defining a System of Systems Engineering and Integration Approach to Address the Navy's Information Technology Technical Authority." Presentation to the 2013 INCOSE symposium. Philadelphia, PA.

Vaneman, Warren and Roger Jaskot. 2013. "A criteria-based framework for establishing system of systems governance." Systems Conference (SysCon), 2013 IEEE International, 491–496. 7, doi 10.1109/SysCon.2013.654992

Wikipedia. 2013, October. s.v. "System of systems engineering." Accessed July 25, 2014. http://en.wikipedia.org/w/index.php?title=System_of_systems_engineering&oldid=579163741

Yarnell, Paul. n.d. "George Washington (SSBN-598), Date and Place Unknown." NavSource Online: Submarine Photo Archive. Accessed July 27, 2014. http://www.navsource.org/archives/08/0859801.jpg

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